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ADVANCED MOISTURE MODELING OF POLYMER COMPOSITES

by

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ABSTRACT

Composite materials absorb moisture from the environment and over time this moisture absorption affects the mechanical performance of the material. In order to determine the long-term moisture effects on the component, representative parts must be tested after having been exposed to an accelerated moisture-conditioning environment. This accelerated environment simulates the worst-case exposure conditions that a part might experience. Currently accepted methodologies for analyzing the time required to condition specimens are limited, only allowing simple geometry and an assumption that diffusivity rates are independent of the flow path or direction. Therefore, a more advanced finite element method is desired. In the current work, a three dimensional model is developed and implemented in commercial finite element code. The parametric study is being conducted for complex shapes, moisture diffusion from any surface, and varying moisture and temperature conditions. The ultimate goal for this research is to determine exposure times for accelerated conditioning that produce the most accurate moisture distribution within the part and minimize over-conditioning of the laminate.

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1. INTRODUCTION

1.1. OVERVIEW

This section explains the research objective and the effects of moisture diffusion upon parts made from composite materials. Understanding moisture diffusion and the need for accurately calculating diffusion in composites to determine the structural strength is crucial to this research and the battery of tests to achieve optimum results.

1.2. RESEARCH OBJECTIVE

Most modern day aerospace vehicles are constructed with at least some components fabricated out of composite materials. With the advancement of technology, the size and number of structural elements made of composites that are used in the construction of large products such as the Boeing Dreamliner is increasing. The private sector and military alike have come to depend upon these composite products to perform in a variety of components under normal and harsh conditions with good reliability, efficient weight, and a reasonable product life. In order to meet these high expectations, aerospace companies must perform rigorous tests on individual components and the structure as a whole to pass stringent regulations. Testing can become very expensive and time consuming. Therefore, reducing the length of time required to perform testing while still obtaining accurate results can save companies money.

1.3. MOISTURE DIFFUSION

It is known that due to the nature of composite materials, moisture will be absorbed from the surrounding environment and this moisture absorption can affect the structural integrity including changing the polymer properties [13]. The loss of structural integrity can be determined by submitting these parts and complete structures to the appropriate physical tests that will analyze the effects of the moisture absorption. It is essential that aerospace companies be able to analyze the effects of moisture absorption upon their structures in the real world environment but for obvious reasons cannot wait years to obtain reliable results. For this reason, parts are placed in accelerated environments for pre-determined periods of time to achieve the same results that would occur during real world service. The amount of time samples are required to be in accelerated environments is determined with either a predefined time or with one-dimensional calculations. A pre-defined soak period can result in a part spending unwarranted time in an accelerated chamber, lengthening research time and possibly costing more than necessary. In addition, because moisture equilibrium is dependent upon relative humidity, steps must be taken to accurately simulate the real world conditions without over-soaking the specimen [10]. A sample that is not soaked long enough to meet real world conditions will show overly optimistic test results, but a part that is over-soaked could produce data which could require that part being over built. The aim of the current research and hence this paper is determination of the desired time soak period through exact analyses of thick composite using the finite element analysis software ABAQUS to accurately evaluate moisture diffusion in polymer composites.

2. BACKGROUND

2.1. OVERVIEW

The background portion of the paper discusses the various types and properties of composite materials, laminate structures used in the aerospace industry, the methods used to evaluate composites, and the moisture diffusion research occurring at Missouri S&T. Additionally, a survey of previous studies and articles providing the foundation for research now and in the future is discussed.

2.2. COMPOSITE MATERIALS

Composite materials consist of at least two substances including a discontinuous and a continuous. The discontinuous or reinforcing material, often times known as the fiber, is stiffer and stronger providing the strength for the composite material. The continuous or matrix is the binder or resin and holds the fiber together [1]. The resin researched is a polymer matrix, a liquid resin converted into a hard and brittle solid through chemical cross-linking. The polymer composites can be broken into two categories: thermoplastic, which through cyclic heating and cooling can be softened and hardened respectively, and thermoset, whose shape after the application of heat or chemicals cannot be non-destructively changed. The negative effects on the composite are primarily on the matrix, possibly on the interface, whereas certain types of fibers are fairly insensitive to the environmental conditions [5].

The authors of the textbook *Analysis and Performance of Fiber Composites Third Edition,* Ararwal, Broutman, and Chandrashekara subdivided composite materials into two basic types: fiber-reinforced or fibrous composites and particle-reinforced composites or particulate composites and then subdivided those classifications further. Particulate composites are commonly made of small particles, such as in the case of particleboard, and can have an orientation that is either random or preferred. Fibrous composites can be multilayer (angle-ply) or single-layer meaning that the composites have the same properties and orientation. Single layer composites can be reinforced with discontinuous fibers, fibers cut into small pieces or chopped, or continuous fibers, fibers with few or no breaks. Properties of composites composed of continuous fibers are higher than those with discontinuous fibers as a result of fewer breaks.

Orientation of discontinuous fiber-reinforced composites can be either random or controlled to give strength in desired directions. Continuous-fiber reinforced composites can be either unidirectional, all the fibers are orientated in one direction, or bidirectional, two directions such as in woven fabrics. For the most part composite materials used in the aerospace industry are multiphase materials made from reinforcing fibers, usually carbon or glass, pre-impregnated (pre-preg) with polymer material or resin system that are combined and cured to create a stronger substance [1].

Multilayered composites are constructed out of numerous layers of plies called lamina stacked on top of each other. Within a ply, the fibers can be unidirectional, bidirectional or in other forms less commonly used. Unidirectional laminates will be the focus of research at Missouri University of Science and Technology (Missouri S&T) located in Rolla, Missouri. Material properties in unidirectional lamina maintain higher strength along the direction of the fibers, whereas perpendicular to the fiber the matrix properties dominate, thus, the strength is weaker in the perpendicular direction.

Most composite structures are not loaded in a single direction, so the laminate structure must be stacked with the lamina's fibers orientated at different angles in order to support the loading. The unique load cases for each component determine the layup, number of layers required, and the fiber orientation of the laminates. Composite laminates are preferred over more traditional materials such as aluminum because of the high strength/stiffness to weight ratios and the high temperature tolerance [1].

2.3. LAMINATE STRUCTURES

Lamina can be stacked in various structures, but the research team from the Mechanical Engineering Department at Missouri S&T is presently only concerned with two types: the 2-phase monolithic and the 2-phase hybrid, chosen because of their usage by the aerospace industry. In the past, the most common structure used by the industry was the 2-phase monolithic while the 2-phase hybrid structure was used mainly for specialized applications. As more technological advances are made upon aircrafts and the loading expectations increase, the use of hybrid structures is becoming more common. Hybrid structures provide improved results over monolithic laminates and allow for additions such as film adhesive packs, metal doublers, IR, and ballistics.

Missouri S&T is researching the monolithic and hybrid laminate structures in two phases. The first or initial phase modeled moisture diffusion in 2-phase monolithic structures. Findings from the first stage will be used as the basis for research with 2-phase hybrid laminate structures. Commonly monolithic refers to products that consist of a single material or are made of multiple materials mixed in such a fashion that the whole product becomes homogeneous (i.e. individual components are no longer discernable).

To distinguish between the 2-phase monolithic and the 2-phase hybrid, for this paper monolithic will be used to refer to a composite structure that uses a single type of reinforcing material and a single type of binder. Hybrid will refer to a composite laminate with multiple types of resins, multiple types of reinforcements, or a combination [1].

Various composite materials can be used in hybrid structures, but future research at Missouri S&T will be mainly focused on hybrid structures that use carbon and glass fibers. The strength properties of glass are lower to some extent than the properties of carbon fiber, but glass fibers are less brittle and cost less than carbon fibers. Consequently, through a proper combination of layers of carbon and glass lamina, a structure can be made with a similar overall strength compared to an all carbon fiber part at a reduced cost. Reducing cost while still maintaining strength is a main driving factor for the push to use hybrid structures.

While the usage of these structures is destined to increase dramatically, analysis is still in the research phase for a number of reasons. First, when modeled as monolithic structures, 2-phase hybrid structures do not "condition" as predicted. Second, the "wet" performance, i.e., performance of the structure after it has absorbed moisture from the environment, is not entirely understood, thus, design values need to be conservative not allowing for full potential results [1]. Third, there is an increased difficulty analyzing the comparison of moisture diffusion to heat transfer in the hybrid structure sample because the moisture concentration is discontinuous between the interfaces of materials with different diffusion coefficients. Methods have been proposed to deal with the third problem including the normalization approach, direct concentration approach, and piecewise normalization approach. Each approach has its own limitations [16].

2.4. MOISTURE ABSORPTION

Moisture absorption in polymer composites can affect the mechanical properties of a part by degrading the fiber matrix interface, microcracking the matrix, changing the stress state, and altering the glass transition temperature [5 & 15]. Over time composite materials absorb moisture from the surrounding environment. In order to ensure reliability of the mechanism and to determine the time that the mechanism can be in a real life environment before moisture absorption damages structural integrity, a variety of tests are performed on samples that have undergone accelerated exposure to simulate "'end of life' moisture content usually defined as service moisture content" [7]. In this research, the test simulates 10 years at 80° F with 82% relative humidity (RH) as this is considered to be a common standard for the worst environment aircrafts will experience.

The following data is obtained from three of the various tests to which the samples are submitted. Tension and compression tests at different angle orientations provide initial modulus and ultimate strength with a function of the moisture and temperature. The interlaminar fracture toughness test creates guidelines for the matrix selection based off delamination resistance. Micro de-bonding tests determine whether the fiber/matrix bond is important in the degradation process [5].

Waiting ten years to test product materials is impractical, so in order to achieve the same results in a shorter period of time composite parts are placed in moisture chambers with an accelerated condition, in this case 160 °F and 95% relative humidity. The amount of time the part must remain in the chamber under accelerated conditions is determined by calculating the moisture content the part would absorb during ten years in real world conditions or the Design Moisture Content (DMC) and then calculating the time required to reach DMC in the accelerated chamber. Since moisture diffusion is extremely slow, thin parts may reach moisture equilibrium while thick parts will never become fully soaked within their service life. The weight of the part with absorbed moisture can be calculated after determining either the quantity of moisture that the part will absorb during ten years or by determining moisture equilibrium taking into account that the moisture equilibrium content is dependent on the RH but is not affected by temperature [1]. The weight equation can determine the amount of moisture in a part.

$$M = \frac{W - W_d}{W_d} X\ 100 \tag{1}$$

where

W= mass of moist material

W_d= mass of dry material

According to the ASTM Standard, mass should be calculated in the following manner. First, the test sample is oven dried and the mass weighed to obtain a base line. Second, the specimen is placed in a conditioning chamber, which has already reached the predefined conditions. Third, at specified time intervals, the specimen is removed from the chamber and placed in a specimen bag until the specimen can reach laboratory temperatures. Fourth, once the specimen reaches laboratory temperature, the specimen is removed from the bag and the surface moisture wiped dry. Fifth, the sample is weighed and then replaced into the moisture chamber until the next weighing [2]. The desired moisture content is reached once the part equals the weight that is calculated using the 1D Fick's' equation. A computational model can be created using Fick's 2nd law of diffusion in 1D to determine the target moisture after ten years. Fick's model could indicate whether a shorter time period in the chamber would obtain the same accurate results as the present mandatory time.

3. PROGRAMS AND MATHEMATICAL EQUATIONS

3.1. COMPUTER PROGRAMS

Computer codes run in the Excel and ABAQUS programs in conjunction with mathematical equations provided the data for this research. Missouri S&T utilizes the Excel program in the moisture diffusion research. The Excel program uses the combination of two computer codes, the W8GAIN developed by the Mechanical Engineering Department at the University of Michigan [10] and ABSORB, which have been combined and coded in Microsoft Visual Basic and then implemented in Microsoft Excel with macros enabled [3]. Although the Excel program is capable of performing multiple methods to compute moisture diffusion including a summation method that uses the ABSORB code, for phase 1 of the Missouri S&T research only the FEA method using Fick's equation for ID diffusion was used as a comparison to ABAQUS results. The equations for one-dimensional moisture diffusion, boundary conditions, calculation of diffusion coefficients, and edge effect can be and were derived using the Fick's equation for 1D diffusion.

3.2. MATHEMATICAL EQUATIONS FOR EXCEL

3.2.1. Fick's 1st Law. Fick's 1st law explains the diffusion or flux of molecules from areas of higher concentration to areas of lower concentration, where flux is proportional to the rate of change of concentration with respect to position [9].

$$J = -D\frac{\partial \emptyset}{\partial z} \qquad (2)$$

where

J is the diffusion flux

D is the diffusion coefficient or diffusivity

∅ is the concentration in dimension of moles per unit length

3.2.2. Fick's 2nd Law. Fick's second law, derived from Fick's first law, allows for the calculation of the moisture content at a given location in the material at any given time. The concentration of the substance in a Δx length of material during a Δt time interval is approximately

$$\left(J(z_0, t_0) - \frac{J(z_0+\Delta z, t_0)}{\Delta z}\right) * \Delta t \tag{3}$$

So the rate of change of the concentration is approximately

$$\frac{\Delta c}{\Delta t} = \left[\frac{\left(J(z_0,t_0) - J(z_0+\Delta z, t_0)\right)}{\Delta z}\right] \tag{4}$$

When taking the limit the equation becomes

$$\frac{\partial c}{\partial t} = -\frac{\partial J}{\partial z}(t_0, t_0) \tag{5}$$

Substituting J from Fick's 1st law gives the equation for Fick's 2nd Law, shown below for the case of one-dimensional moisture diffusion.

$$\frac{\partial c}{\partial t} = D_z \frac{\partial^2 c}{\partial z^2} \tag{6}$$

where

c is the moisture concentration

D_x is the moisture diffusion coefficient

z is the distance through the thickness

t is the time

For an infinite plate (height and width >> thickness) the boundary conditions become:

$$c = c_i \qquad 0 < z < h \qquad t \leq 0 \tag{7}$$

$$c = c_a \qquad z = 0; z = h \qquad t > 0 \tag{7a}$$

Determining how long parts must be conditioned to reach moisture equilibrium is a major goal of the research. The time equation shown below can be used to determine when moisture equilibrium reaches 99.9%. Thickness and the diffusivity coefficient of the part must be known in order to use the time equation. S equals the thickness of the sample for a part exposed on two surfaces and S equals two times the thickness of the part for a sample exposed on only one surface.

$$t_m = \frac{0.67S^2}{D_z} \tag{8}$$

3.2.3. Calculation of Diffusion Constants. The Excel based program with a 1D Fick's Equation includes methods for determining the diffusion through a plate, the diffusion coefficients, and moisture equilibrium at any temperature/relative humidity (T/RH). Equation 9 shows how to find the modified diffusion coefficient.

$$D_T = d * exp^{\frac{c}{T_d + 459.67}} \tag{9}$$

where $d = \frac{D_{TL}}{exp^{\left(\frac{c}{T_L + 459.67}\right)}}$ (9a)

$$c = \frac{log\left(\frac{D_{TL}}{D_{TH}}\right)(T_H + 459.67)(T_L + 459.67)}{(T_L + 459.67) - (T_H + 459.67)} \tag{9b}$$

where

D_{TL} is the diffusivity at the lower temperature

D_{TH} is the diffusivity at the higher temperature

D_T is the diffusivity at the desired temperature

T_L is the lower temperature

T_H is the higher temperature

T_d is the temperature at which diffusivity is needed

459.67 is the conversion of the temperature from Fahrenheit into the Rankin Scale.

3.2.4. Calculation of Moisture Equilibrium. The moisture equilibrium content Meq at different relative humidity (RH) can be interpolated given two data points and the following equations:

$$Meq = a * RC * RH^b \tag{10}$$

$$a = \frac{M_{eq\_L}}{RC*RH^b} \quad b = log_{\left(\frac{RH_L}{RH_H}\right)}\left(\frac{M_{eq\_L}}{M_{eq\_H}}\right) \tag{10a}$$

where:

Meq is the moisture equilibrium at the desired relative humidity,

Meq_L is moisture equilibrium at the lower temperature,

Meq_H is moisture equilibrium at the higher temperature,

RC is the resin content,

RH_L and RH_H are the low and high relative humidity respectively.

Inputs required for the program include the laminate thickness, size of the plate, relative humidity, temperature, the initial moisture content, resin content, and soak interval times. Finite or infinite plates can be run in the Excel program. The program does not actually measure the moisture absorbed through the edges but instead modifies the diffusivity coefficient using the edge correction factor. A finite plate allows for more moisture to be absorbed than an infinite plate given the same amount of time and same ambient surrounding conditions.

The edge correction factor does not calculate the moisture distribution in the direction of the edges but instead modifies the diffusion coefficient through the thickness to try and take into account the added moisture intake. An edge correction factor must be used unless no moisture diffusion from the edges occurs, a situation that is only possible if the edges are impermeable (sealed) or if the plate was infinite.

3.2.5. Edge Effect. The effects of moisture distribution must be taken into account for parts where the length and width compared to the thickness is not notably larger. For a part constructed out of a homogeneous material, the edge effect equation is written as

$$D_m = D_z\left(1+\frac{h}{l}+\frac{h}{w}\right)^2 \tag{11}$$

However, for a component with orthotropic properties, the edge effects equation becomes

$$D_m = D_z\left(1+\frac{h}{l}\sqrt{\frac{D_x}{D_z}}+\frac{h}{w}\sqrt{\frac{D_y}{D_z}}\right)^2 \tag{12}$$

where

D_m is the modified diffusivity coefficient through the thickness

D_x, D_y, D_z are the diffusivity coefficients through the thickness and in the directions of the exposed edges

h is the thickness of the part

l and w are the dimensions for the length and width of the part

3.3. FICK'S 2ND LAW IN 3D

The basic 1D Fick's equation has been useful in collecting data in the past, but there are limitations. Two of the limitations are (1) during short periods of time the Fickian method tends to overestimate moisture absorption in panels [6] and (2) real world parts are too complex for the four main restrictions: in order for the equation to be accurate the plate thickness must be constant, the diffusivity constant must be the same through the thickness, the plate is either considered infinite (in the width and length directions) or has a correction factor for the non infinite plates, and without a correction factor the moisture can only be applied to two opposite surfaces. The edge effect equation allows for consideration of non-infinite plates but the other limitations of the 1D Fick's equation are still present. Consequently the more general 3D Fick's equation must be utilized.

$$\frac{\partial c}{\partial t} = D_{11}\frac{\partial^2 c}{ax^2} + D_{22}\frac{\partial^2 c}{ay^2} + D_{33}\frac{\partial^2 c}{az^2} + \left(D_{23} + D_{32}\right)\frac{\partial^2 c}{\partial y \partial z} + \left(D_{31} + D_{13}\right)\frac{\partial^2 c}{\partial x \partial z} + \left(D_{12} + D_{21}\right)\frac{\partial^2 c}{\partial z \partial y}$$

Where c=c(x,y,z,t), (13)

meaning that c is the moisture concentration and is a function of the spatial coordinates and time, and D=D(t) is the rate of diffusion [16]. The moisture diffusion is largely controlled in the three primary directions:

$D_x = D_{11}$ is the diffusivity parallel to the direction of the fiber

$D_y = D_{22}$ is the diffusivity perpendicular to the direction of the fiber

$D_z = D_{33}$ is the diffusivity through the thickness of the sample

The diagonal terms were ignored resulting in the following three-dimensional equation.

$$\frac{\partial c}{\partial t} = D_{11}\frac{\partial^2 c}{\partial x^2} + D_{22}\frac{\partial^2 c}{\partial y^2} + D_{33}\frac{\partial^2 c}{\partial z^2} \tag{14}$$

3.4. ABAQUS PROGRAM

Although possible, calculating the 3D Fick's equation by hand is both cumbersome and time consuming, so is impractical for anything but the simplest of scenarios. Therefore, the use of the software applications for finite element analysis (FEA) such as ABAQUS, is a more practical route. Instead of using an analytical solution, an FEA solution using the Finite Element Equation can be implemented to estimate the moisture concentration within a part using a discrete model made up of piecewise continuous functions defined using a finite number of elements [12]. The use of 3D FEA software once implemented can allow for complex shapes, allows moisture to be applied to any surface, is faster than hand calculations, allows for diffusivity to be varied in the different axis and, hopefully allows for a more accurate moisture profile through the test part.

3.4.1. Finite Element Equation.

$$[K]\{c\} + [C]\{\dot{c}\} = \{F\} \tag{15}$$

Upon integration in time domain using Finite Difference method

$$([C] + \Delta t[K])\{c\}^{t+\Delta t} = [C]\{c\}^{t} + \Delta t\{F\} \tag{16}$$

where [K] represents the moisture diffusivity matrix,

[C] the moisture velocity matrix,

{F} the external moisture flow vector,

{c} the nodal moisture content and

$\{\dot{c}\}$ the rate of change of nodal moisture content [14]

3.4.2. Governing Equations in ABAQUS. The governing equation in ABAQUS allows for mass diffusion, which is driven by temperature, concentration, and pressure gradient. The equation follows the mass conservation equation for uniform region of the volume V and surface area S.

$$\int \frac{dc}{dt} dV + \int q * n * dS = 0 \tag{17}$$

where C, q_i, and n are the humidity function, moisture flow density, and outward normal of the surface, respectively. The weak form can be obtained from the previous equation by using the weighted residual method and integrating by parts. Φ denotes the thermodynamic potential [15].

$$\int \left(\frac{\partial q}{\partial x} + \frac{\partial c}{\partial t}\right) \delta\Phi dV = 0 \tag{18}$$

This equation can then be integrated by parts and by introducing the equation from Fick's 1^{st} Law the following equation can be derived.

$$q = -D\left[\frac{\partial\Phi}{\partial x} + k_s \frac{\partial}{\partial x} lnT + k_p \frac{\partial P}{\partial x}\right] \tag{19}$$

where D , s, T, and k_p, are the moisture diffusion coefficient (mm^2/s) under temperature T, solubility, temperature, stress factor, and stress, respectively. k_s denotes the Soret impact factor induced by the temperature gradient. P is defined as –trace (σ) /3. Our study does not take into account pressure driven diffusion and temperature driven diffusion which means K_s=K_p=0. The governing equation in ABAQUS reduces to be the same as Fick's Second Law.

4. ANALYSES

4.1. CONVERGENCE CASES

A variety of analyses were run in ABAQUS and then compared to the output of the Excel program to verify that the ABAQUS model was producing accurate results. Once the model was verified, more complex analyses were conducted to determine the capabilities and limitations of ABAQUS [15].

4.1.1. Experimental Sample. A suitable sample with the dimensions for width x height x thickness of 3" x 3" x 1" is used for testing. Moisture is applied to the sample on the top surface and on the four sides while the bottom is insulated. Diffusivity constants in the three primary axes are shown in Table 4.1. Diffusivities for unidirectional composites are defined as:

$D_x=D_{11}$ is the diffusivity parallel to the direction of the fiber in a lamina

$D_y=D_{22}$ is in the direction perpendicular to the fiber orientation in a lamina

$D_z=D_{33}$ is diffusivity through the thickness of a stacked laminate.

The Excel program uses standard units with the diffusivity calculated using inches^2/second, whereas ABAQUS uses the metric system and the analyses are run in hour increments. Experimental diffusivity constants for two different temperatures are provided. Using these two data points and equation 8, diffusivity for other temperatures can be interpolated.

Experimental moisture equilibrium was provided for the two different inputs of relative humidity. Since moisture equilibrium content is not dependent upon the direction of the fibers, the equilibrium value was the same in different directions.

Therefore, only two values were needed for the moisture equilibrium. Given two values and the use of Equation 9 moisture equilibrium for different other relative humidity can be determined. The experimental data provided in standard units (%) is shown in Table 4.2. Conversion from standard to metric units of parts per million (ppm) is equivalent to 1 milligram of water per kilogram of the composite (mg/kg). Using constants from Tables 4.1 and 4.2 and Equations 9 and 10 for interpolation the following analyses were performed.

Table 4.1 Diffusivity Constants for Two Temperatures in the Primary Axes

Temp.	D_x (in^2/sec)	D_x (mm^2/hr)	D_y (in^2/sec)	D_y (mm^2/hr)	D_z (in^2/sec)	D_z (mm^2/hr)
80°F	3.4×10^{-11}	7.90×10^{-5}	3.20×10^{-11}	7.43×10^{-5}	2.30×10^{-11}	5.34×10^{-5}
160°F	8.2×10^{-10}	1.90×10^{-3}	7.60×10^{-10}	1.77×10^{-3}	4.95×10^{-10}	1.15×10^{-3}

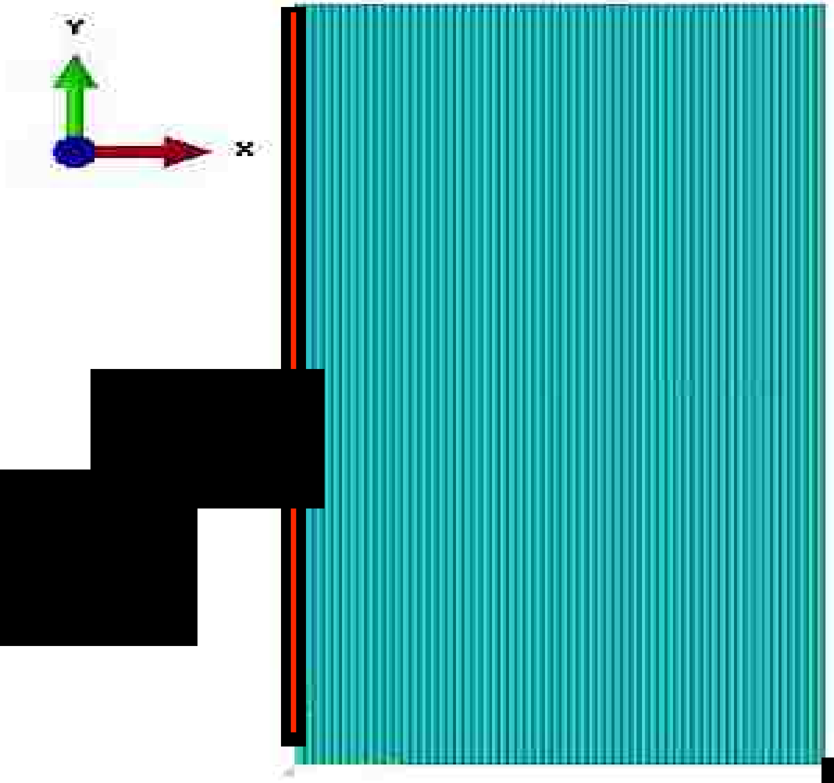
Table 4.2 Moisture Equilibrium Constants for Relative Humidity

Moisture Equilibrium Constants		
Relative Humidity	Moisture Eq. (%)	Moisture Eq. (ppm)
0.80	1.18	11,800
0.95	1.70	17,000

4.1.2. Excel Convergence. The first analysis was a mesh convergence run in the Excel program to determine the sufficient number of elements through the part needed to obtain accurate results. Three different element amounts were chosen for the analysis: the minimum recommended amount for the program of 30 elements, then 100 elements, and finally the maximum allowable amount of 300 elements. The Excel convergence analysis was executed with the following inputs: the diffusivity coefficient in the D_x direction (8.20×10^{-10} mm^2/sec), width of 3 inches, and soak time of 120 days at the accelerated conditions of 160°F and 95% relative humidity resulting in a moisture equilibrium of 1.7%. Since the program was run using a symmetric analysis (moisture applied to opposite sides) the output was only generated for half the thickness or 1.5 inches, thus the element sizes become 0.05", 0.015" and 0.005" for the three different numbers of elements.

4.1.3. ABAQUS Convergence. Prior to comparing results of ABAQUS to Excel results a mesh convergence in ABAQUS was performed to ensure that the ABAQUS model produced accurate results and was not creating errors due to poor element size. At least three convergence analyses were plotted to determine if convergence was realized. Once two runs with different size meshes produced the same results, the mesh size was considered adequate to obtain accurate data. The mesh study model was constructed as a 2D model with a distance of 1.5 inches or 38.1 millimeters in the X-direction, which again because of the symmetry was half the width of the sample part, and has a height of 3 inches or 76.2 millimeters in the Y-direction. Since diffusion was only taken into account in the X-direction, the moisture boundary condition was applied to the left edge of the 2D model. The convergence was then run in ABAQUS with D_x diffusivity and the same conditions for soak time, temperature, relative humidity, and metric constants as the Excel convergence study. No boundary conditions were applied to the edges since ABAQUS assumes that all edges without boundary conditions are insulated (no moisture applied). For all the analyses the element height (the Y-direction) was equal to the height of the model while the different runs used 3, 5, 11, 17, and 33 elements in the X-direction.

[redacted]



[redacted]

[redacted]

[redacted]

Figure 4.1 Half Model in ABAQUS for Convergence Analysis

4.2. COMPARISON OF EXCEL RESULTS TO ABAQUS RESULTS

4.2.1. ABAQUS 2D Comparison to Excel. Upon completion of the convergence tests in both Excel and ABAQUS, analyses were performed to compare the results from the Excel program to that of ABAQUS. The model ran for the first analysis with the same conditions as those used in the convergence studies: 120 days at the accelerated conditions of 160°F and 95% RH with the diffusivity only taken into account in the X-direction. The 1D values from the Excel program were considered to be accurate as the calculations were based upon 1D Fick's FEA methods successfully used for years thus the Excel results verified the results from ABAQUS. After running the analysis in ABAQUS, the values from the element nodes through the thickness (X-direction) were graphed in Excel and compared to the output generated in the Excel program using the same parameters.

The ABAQUS model needs to produce accurate results for both relatively short periods of time (120 days) and for much longer periods so another analysis was run to simulate 10 years or 87,600 hours using the same model. The 10 year simulated analysis performed using the real world conditions of 80°F with 82% RH and the boundary conditions were applied in the same manner as the 120-day analysis. The diffusivity coefficients used in the Excel program and ABAQUS were pulled directly from Table 4.1. Since the relative humidity used in ABAQUS convergence analysis was different than the one used to generate experimental data for the moisture equilibrium, the experimental data was interpolated using equations 10 and 10a resulting in a moisture equilibrium constant of 1.24% or 12,400 ppm. Further analyses were performed with the 2D model using the remaining two diffusivity coefficients at 160°F. Analysis for the D_y

diffusivity was performed in the same manner as the analyses for D_x. The model for the D_z diffusivity analysis was modified so that the width in the X direction became 0.5 inches or 12.7 millimeters. Symmetry allowed for half the thickness to be modeled, so the test sample was one inch thick.

4.2.2. ABAQUS 3D Comparison to Excel. Data from the 2D model analyses in ABAQUS confirmed that the program could produce accurate results, so a 3D model was built to determine if the same accurate results could be produced. If the 3D experimental model proved reliable, full 3D models could be created allowing research on more complex moisture diffusion. The FEA model created from the 2D model to be used in the 3D analyses had the following dimensions: 38.1 mm (X direction), 76.2 mm (Y direction), and 12.7 mm (extruded in the Z direction from the 2D model). Figure 4.2 exhibits sixty elements in the X direction of the model (left side view) and the same model with the boundary condition applied to the left edge (right side view).

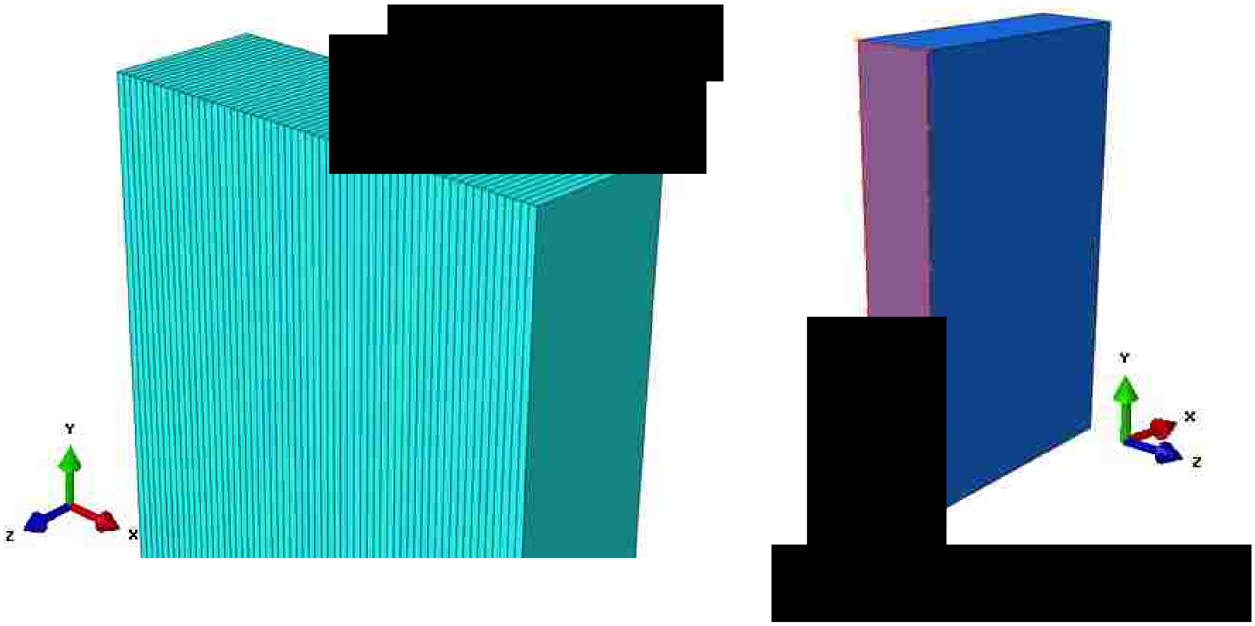


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Figure 4.2 3D Model Analyzing Moisture Concentration in the X Direction

D_x and D_y diffusivities through the 60 elements in the X-direction were analyzed. Because the change in moisture concentration was calculated in only one dimension, the size of the elements in the Y and Z directions did not alter the results. The two remaining dimensions of the model were assigned only one element reducing computation time. Both cases were run under the real world conditions of ten years using the same constants as explained previously for the 2D cases. Inputs for the D_z diffusivity case included 120 days with the same accelerated conditions previously described in the 2D analysis, boundary condition applied along the surface of the model on the XY plane, and the 20 elements created through the thickness in the Z direction as can be seen in Figure 4.3. Twenty elements were consistent with the mesh convergence and analyzing the D_z diffusivity in the Z direction was consistent with the sample part. For the 3D analysis, as in the previous two analyses, there was only one element in the other two directions.

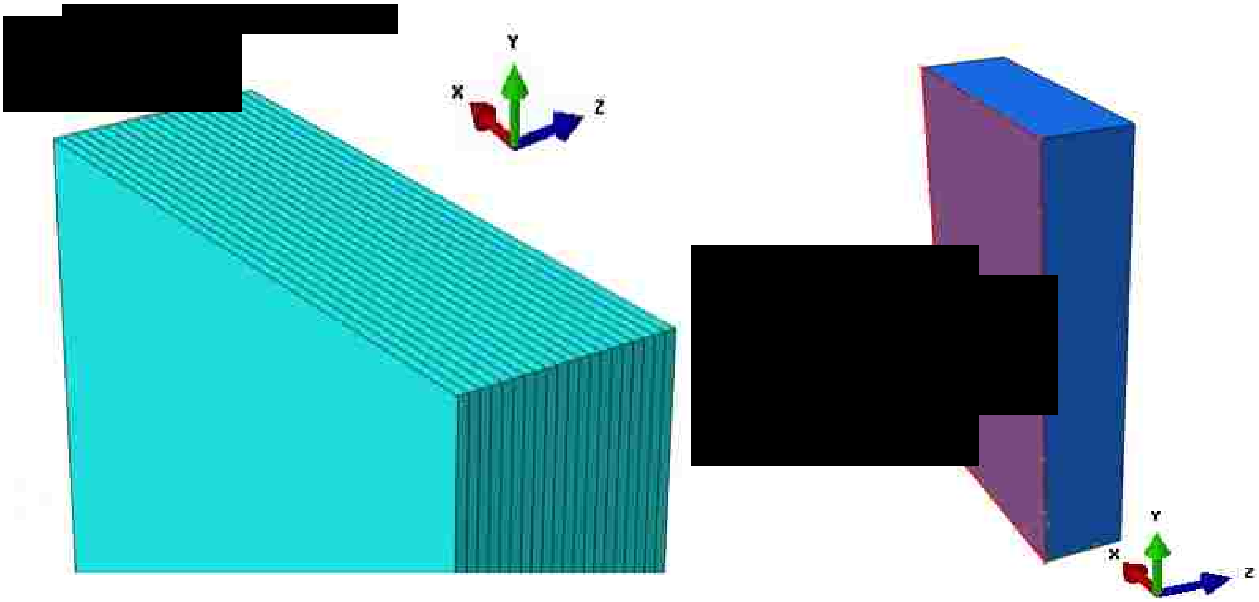
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Figure 4.3 3D Model Analyzing Moisture Concentration in the Z Direction

4.3. COMPARISON OF FINITE AND INFINITE PLATES

4.3.1. Edge Effect Using Correction Factor Equation. Finite and infinite plates were compared to determine how consideration of edge effects influenced the results. If the Excel program is run as an infinite plate, the dimensions of width and length are 1 x 10^6 inches; for dimensions smaller than 1.0 x 10^6, the program uses the correction factor. In the comparison, the width and height dimensions for the finite plate in Excel was 3 x 3 inches. The thickness of both infinite and finite plates was one inch, inputs for the accelerated conditions were 160°F with 95% RH, and running time of 120 days or 2880 hours. A model created in ABAQUS for infinite and finite plates used the same dimensions of 38.1 x 38.1 x 12.7 mm for both. In ABAQUS, the infinite plate does not need to conform to the 1 x 10^6 dimensions because surfaces with no provided conditions are considered to be insulated resulting in the same boundary conditions as the Excel program. Because of symmetry, the ABAQUS model was halved in all directions requiring fewer total elements and subsequently allowing faster run times.

No moisture was applied to the sides of a model in ABAQUS for the first comparison of finite versus infinite plates; instead using the edge effect equation, Equation 12, a corrected diffusion coefficient was obtained and applied to the model properties. The modified diffusivity coefficient for Excel was 1.375 x 10^{-9} in^2/sec and for ABAQUS 3.194 x 10^{-3} mm^2/hr. The moisture equilibrium value remained 1.7% in Excel and 17,000 parts-per-million in ABAQUS. Diffusivity was still taken into account in a single direction but could be used to compare the ABAQUS results to the Excel results with edge effects taken into account.

4.3.2. Edge Effect with Fully Applied Boundary Conditions for Homogenous Material Properties. Moisture boundary conditions were applied in the second comparison (shown in Figure 4.4) to the sides of the model in ABAQUS but did not use the modified diffusivity coefficient for edge effects. Two cases, one with homogeneous material properties throughout the plate and one with orthotropic material properties were run with the boundary conditions previously described. For the homogeneous model, the D_z diffusivity coefficient for accelerated conditions was applied in all directions and then moisture boundary conditions were applied to three surfaces. Sixty elements were created through the longer dimensions of the model and 20 elements through the thickness, the Z-direction.

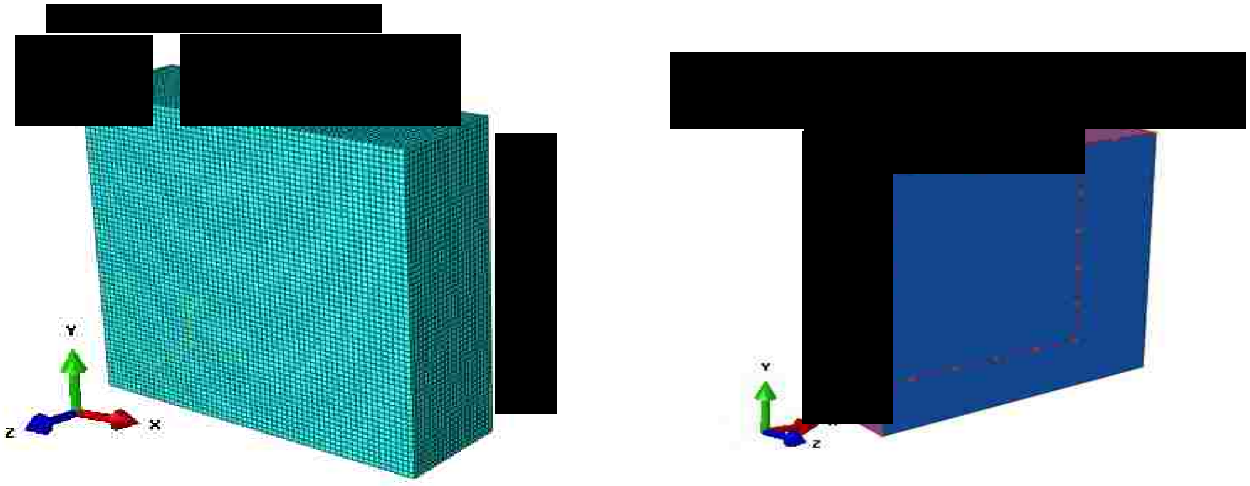
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Figure 4.4 3D Model for Comparison of Infinite vs. Finite Plates

Values of the nodes through the thickness were graphed at several locations from the edge of the plate inward. The cross sectional graphs did not produce a clear comparison between the ABAQUS and the Excel results so values of all the nodes were pulled from the inner surface in the X-Y Plane where the nodes were not exposed to moisture. All of the node values were averaged producing a single curve that was graphed to show the moisture concentration through the thickness of the part. The moisture curves created by ABAQUS and from the Excel output were compared.

4.3.3. Edge Effect with Fully Applied Boundary Conditions for Orthotropic Material Properties. Using the same model in ABAQUS, the next analysis ran with the same conditions but orthotropic material properties are applied to the model instead of homogeneous. In addition, the Excel program was modified to allow for the calculation of edge effects using the equation for orthotropic models. The diffusivity coefficients for D_x, D_y, and D_z are shown in Table 4.1 for both Excel and ABAQUS. Moisture concentration through the thickness was pulled from the nodes on the model after completing the analysis of the orthotropic material properties just as was done in the homogeneous material properties analysis. Values from the nodes were averaged producing two curves for the effects of the moisture diffusion from the edges with diffusivity of D_x and D_y.

4.4. COMPARING SOAK TIME BETWEEN REAL WORLD CONDITIONS AND ACCELERATED CONDITIONS

4.4.1. Comparing Soak Time for Real World vs. Accelerated Conditions to Obtain the Same Average Moisture Content. The study’s ultimate goal is the determination of exposure times for accelerated conditioning that produce the most accurate moisture distribution within the part while minimizing over-conditioning of the laminate. Although conditioning a sample at an elevated temperature and relative humidity decreases the amount of time required to absorb moisture, the part can become over-soaked compared to parts exposed to the relative humidity in the real world because the moisture equilibrium is dependent on relative humidity. Consequently the process of accurately soaking the part is not as simple as placing the part in a conditioning chamber and waiting a set period of time. Considering the complexity of the problem, the moisture diffusion was considered to travel in one direction and the 3D model with the homogeneous material properties was used.

The simplest method for obtaining a sample part that might be equivalent to a real world part is to soak the part until the average moisture equilibrium through the part is equal to that which would be obtained after the predetermined time in the field. By running the sample part used in this research in ABAQUS, the average moisture content with the conditions of ten years at 80°F and 82% RH can be obtained. Then the model can be run using the diffusivity for the accelerated conditions of 160°F and 95% RH until the average moisture content through the thickness is the same. Limitations of soaking the part using this method will be shown in the result section.

4.4.2. Variable Accelerated Conditions to Obtain Equivalent Moisture Content Through the Part. When the higher relative humidity of 95% was used in the conditioning chamber the moisture equilibrium for the sample was 17,000 ppm, but the moisture equilibrium at the real world humidity of 82% was only 12,436 ppm, meaning that, at least near the surface, the sample was over-conditioned compared to the real world part. Therefore, to create moisture content through the sample that was as accurate as possible several analyses were run in ABAQUS with accelerated conditions that varied over time. All of the runs were executed first with conditions of 160°F and 95% RH. Some of the cases were then run with a decreased relative humidity of only 82% but with the same temperature. In an effort to reduce testing time as much as possible while still maintaining the same accurate results other cases were run with a relative humidity of

82% and a higher temperature where the data was extrapolated causing the rate of diffusion to increase. Although a higher temperature reduced the time for the desired diffusion to occur use of excessively high temperatures could cause the properties of the composite to change negating the analysis results. Thus, the maximum temperature that can be used to increase the diffusion rate is dependent upon the limitations of the particular composite.

When creating the model, the initial moisture equilibrium content was set when the material properties were defined. An amplitude curve was used to change the moisture equilibrium after the analysis started. The amplitude curve used with the boundary condition was not for the environment relative humidity but instead for the moisture equilibrium of the part. Creating the amplitude curve was not as simple as using the change in relative humidity. Since the change in moisture equilibrium is not a linear change with the relative humidity, Equation 9 was used to find the change in moisture equilibrium with respect to the initial moisture equilibrium creating a value used in the amplitude curve. The initial amplitude of the cases was 1 but became 12436 /17000 = 0.732 at the desired time step in order to change the relative humidity from 95% to 82%. Changing the diffusivity coefficient in the model due to a change in temperature was carried out in a different manner than changing the moisture equilibrium. When defining the material properties, the diffusion constants were defined as temperature-dependent. The diffusion constants were entered for the different temperatures used during the analysis. During the actual running of the analysis, a temperature boundary condition was applied, which when changed at the desired time caused the correct diffusion coefficient for that temperature to be used.

5. RESULTS AND DISCUSSION

5.1. MESH CONVERGENCE STUDIES

A number of analyses were run comparing ABAQUS and Excel results to confirm the reliability of the ABAQUS program. Section 5 includes mesh convergence studies of Excel, ABAQUS, and the comparison between the two: including a comparison between infinite and finite plates, edge effects for homogenous and orthotropic materials, and soak times for accelerated conditions versus real world conditions.

5.1.1. Excel Element Convergence. Mesh convergence in Excel was first performed for a 3-inch sample. Using symmetry of the sample, the moisture content was determined for 1.5 inches through the thickness. Figure 5.1 shows the results of the convergence study using first 30 elements, then 100 elements, and finally 300 elements. For better clarity, the graph only shows from the surface to a depth of 0.30 inches deep. The convergence test with thirty elements shows a slightly higher moisture intake through the thickness than the other two cases of 100 and 300. The next two tests with 100 and 300 elements show the curves matching up sufficiently to produce accurate results for the element size. Modeling 1.5 inches or half the thickness of the sample with 300 elements results in an element thickness of 0.005 in.; a thickness used in all Excel comparisons for the research.

5.1.2. ABAQUS Element Convergence. Once data for the mesh convergence analysis in Excel was available, a mesh convergence analysis in ABAQUS was performed using five different element amounts through the thickness starting with two, then five, eleven, and finally thirty-three. The first two cases, two elements and five elements showed deviations, see Figure 5.2. A higher concentration was indicated in the case of two elements and a lower concentration nearer to the left edge in the case of five elements. The remaining cases showed the results converging upon each other. Upon completion of the ABAQUS element convergence analysis, 60 elements were determined to be sufficient. Cases with fewer elements converged so increasing the number of elements would not change the results but an increase produced a more standardized element size of 0.635 mm rather than $1.15\overline{45}$ mm.

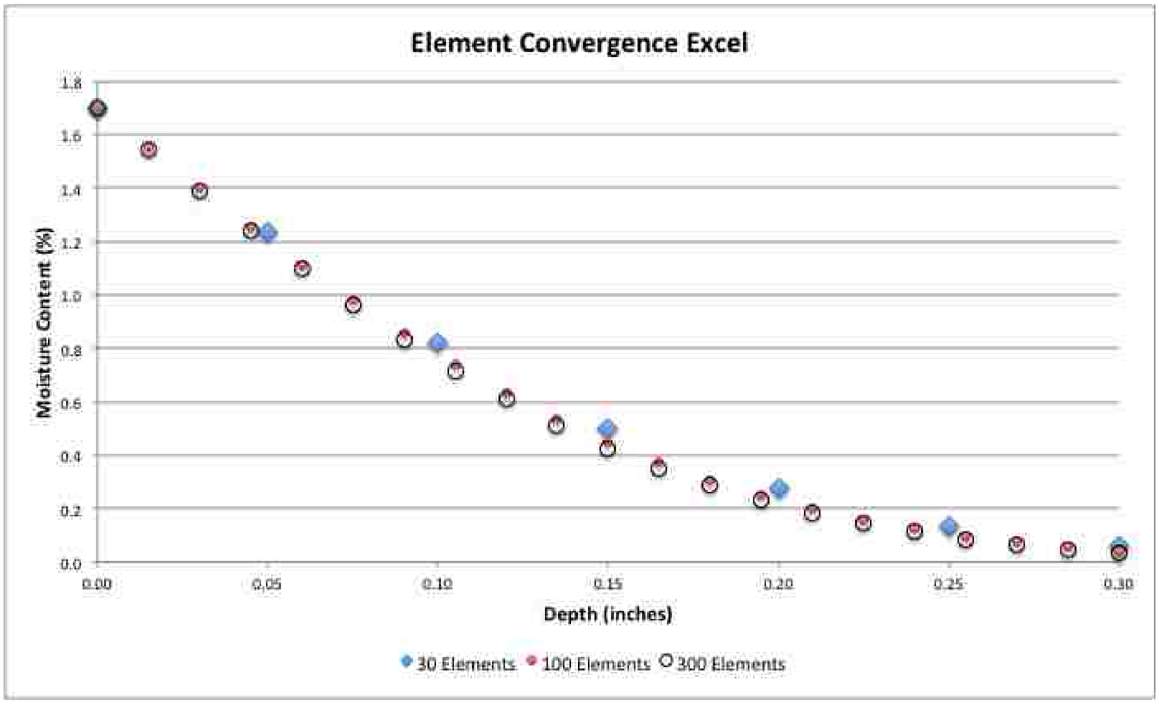

Figure 5.1 Mesh Convergence in Excel Using 30, 100, and 300 Elements

5.2. EXCEL VS. ABAQUS COMPARISON

5.2.1. 2D ABAQUS Model Comparison to Excel.

After completion of the mesh convergence studies in both Excel and ABAQUS, a case was run in ABAQUS. Data produced from the case was compared to the Excel output to verify the accuracy of the ABAQUS values. The first comparison was for a sample of 1.5 inches (38.1 mm) or half the thickness with the accelerated conditions in the D_x direction for 120 days.

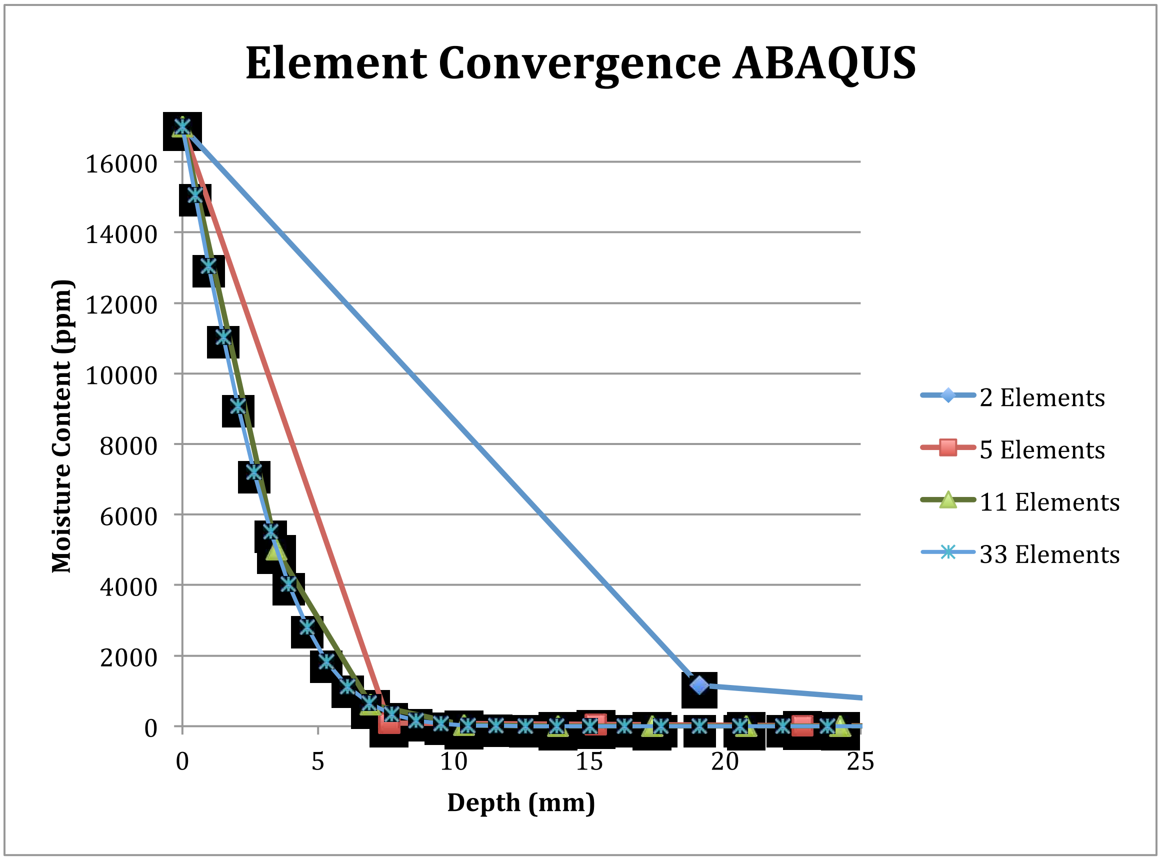

Figure 5.2 Mesh Convergence in ABAQUS Using Multiple Element Sizes

Figure 5.3 shows the results for the D_x diffusivity. For better clarity in the graph, the X-axis was scaled to show only 15 millimeters instead of the half thickness of 38.1 millimeters. No figure was included in the paper for the D_y diffusivity analysis as the results were similar to the results of the D_x diffusivity analysis case. Figure 5.4 displays the results for the D_z diffusivity analysis with a thickness of only 0.5 inches (12.7 mm).

Results from the model in ABAQUS were known to be accurate since the curves of all the analyses fit with the curves from the Excel program. Figure 5.5 shows a visual output produced by ABAQUS using the D_x constant.

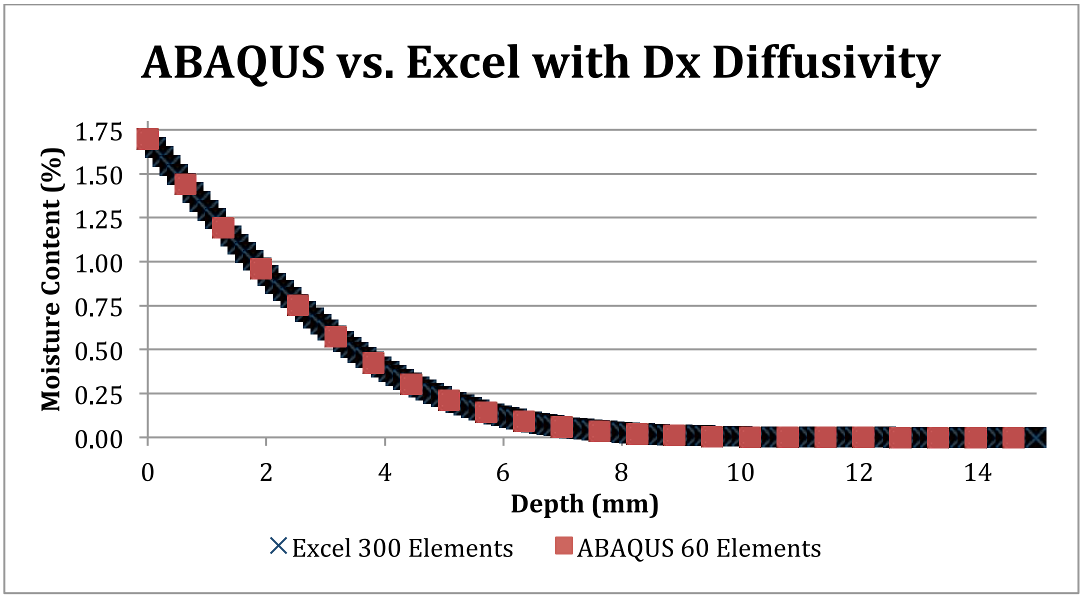

Figure 5.3 Comparison of Excel to ABAQUS with D_x Diffusivity
(120 Days Accelerated)

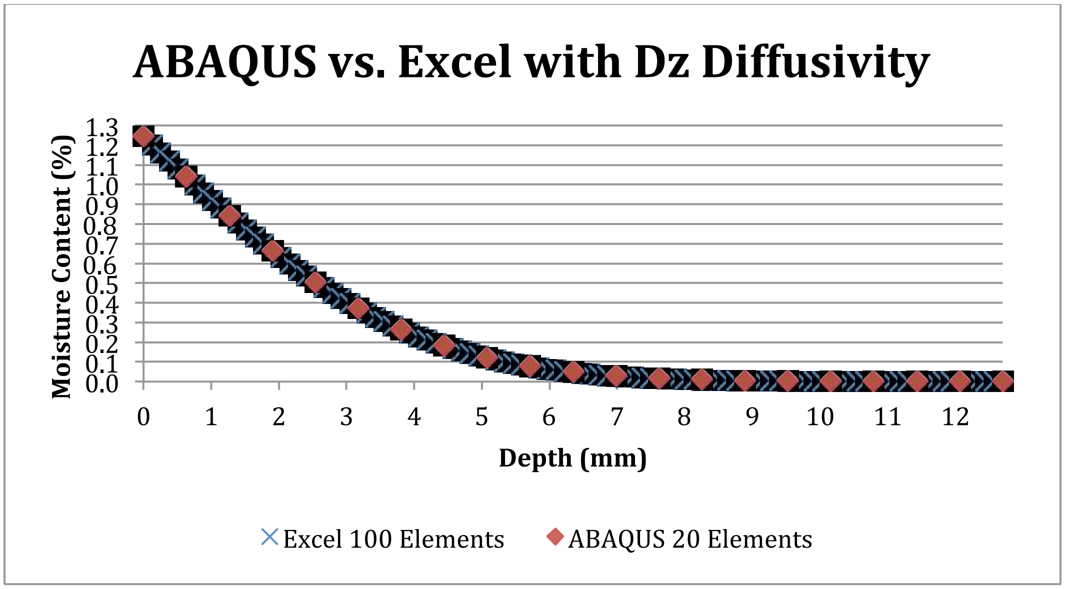

Figure 5.4 Comparison of Excel to ABAQUS with D_z Diffusivity (10 Years)

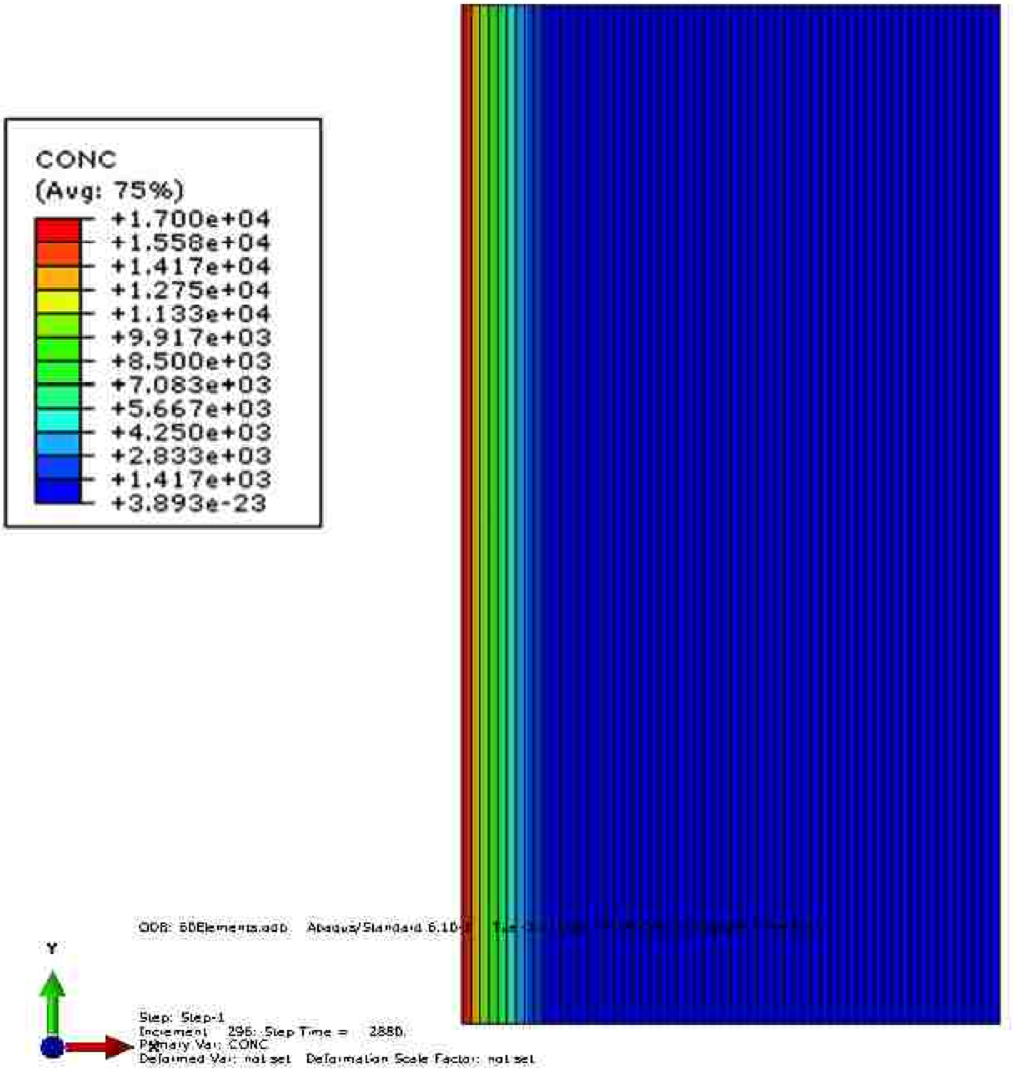

Figure 5.5 Diffusion Through 38.1 mm Thickness with D_x Coefficient

5.2.2. 3D Model Comparison Between Excel and ABAQUS. The next analysis was a comparison of the 3D FEA model to the moisture output of Excel. Figure 5.6 shows the real world conditions of 80°F and 82% RH for 10 years. The sample's comparison in the Z direction used the half model measurement of 0.5 inches or 12.7mm. As expected accurate results were shown between the comparison model created in the

Excel program and the ABAQUS model once again verifying that the 3D model in ABAQUS is capable of producing accurate results. Figure 5.7 shows a visual output of the 3D model with the moisture diffusing in the Z direction.

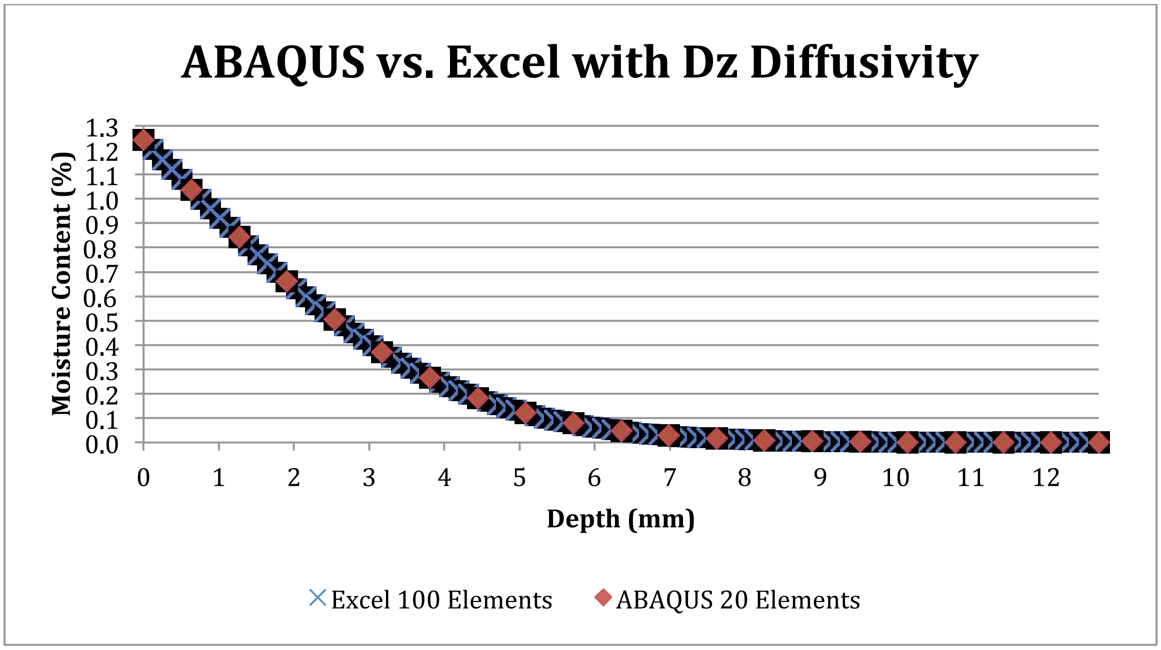

Figure 5.6 3D Model Comparisons (10 Years)

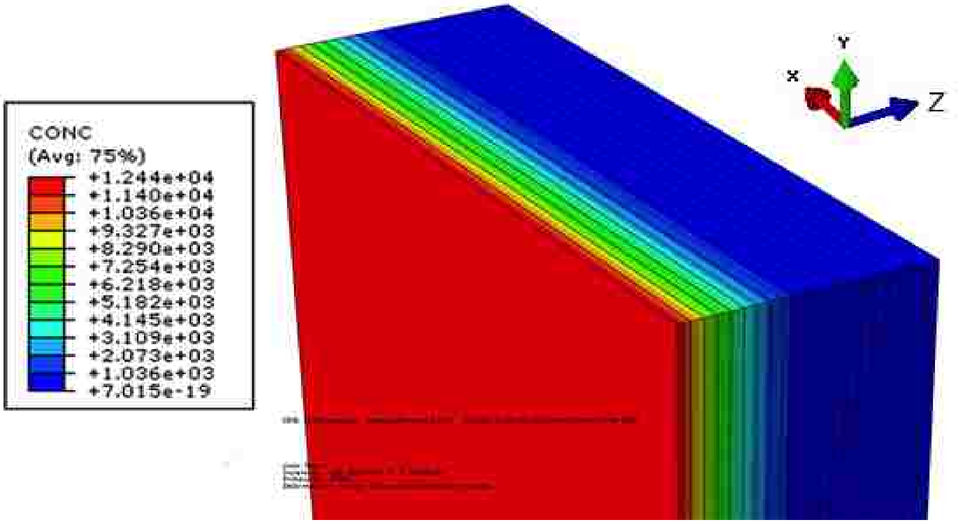

Figure 5.7 3D ABAQUS Model Showing Diffusion in the Z Direction

5.3. INFINITE VS. FINITE PLATES

5.3.1. Excel and ABAQUS Comparison Using Edge Effect Equation. The classic method for dealing with moisture that penetrates through the edges of a part uses two equations that modify the diffusivity coefficient: see Equation 11 for homogenous and Equation 12 for orthotropic material properties. Figure 5.8 shows the analysis of an infinite plate and finite plate run in both Excel and ABAQUS with results that agree with each other. As can be seen on the graph, the finite plate adhered to the moisture theory by absorbing more moisture through the thickness than through the infinite plate. However, the comparison between the infinite and finite plates in Excel and the comparison between the infinite and finite plates in ABAQUS simply show that ABAQUS can run using the modified diffusivity coefficient with moisture traveling in

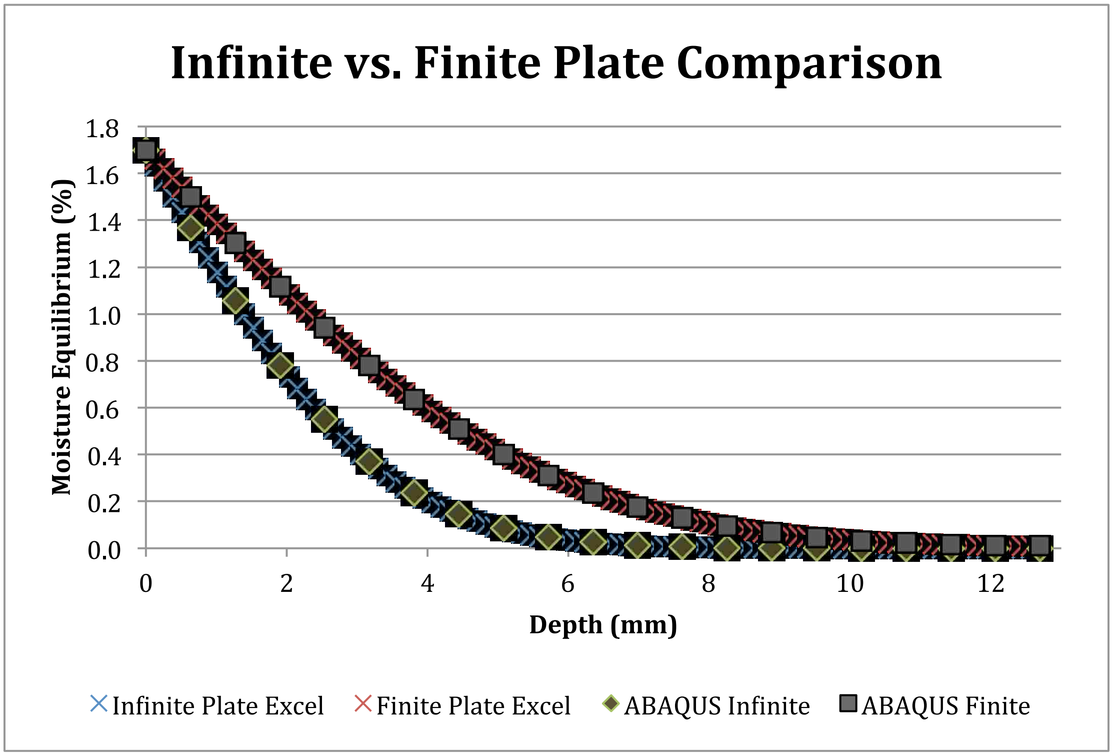

Figure 5.8 Edge Effects Infinite vs. Finite Plate Between ABAQUS and Excel

a single direction. Given the 3D capabilities of FEA, a model with moisture boundary conditions actually applied to the edges of the sample was performed.

5.3.2. Edge Effect With Applied Boundary Conditions for Homogeneous Model. Figure 5.9 is a visual output from ABAQUS displaying an eighth of the sample homogeneous model with dimensions of 3x3x1 inches, D_z diffusivity coefficient for 120 days of accelerated conditions, and moisture boundary conditions applied to all surfaces that would be external for the full model, mainly the back and two sides. 3D capabilities of ABAQUS were implemented and the results compared to the results of moisture applied to the edges using the 1D method where the edge correction factor was applied.

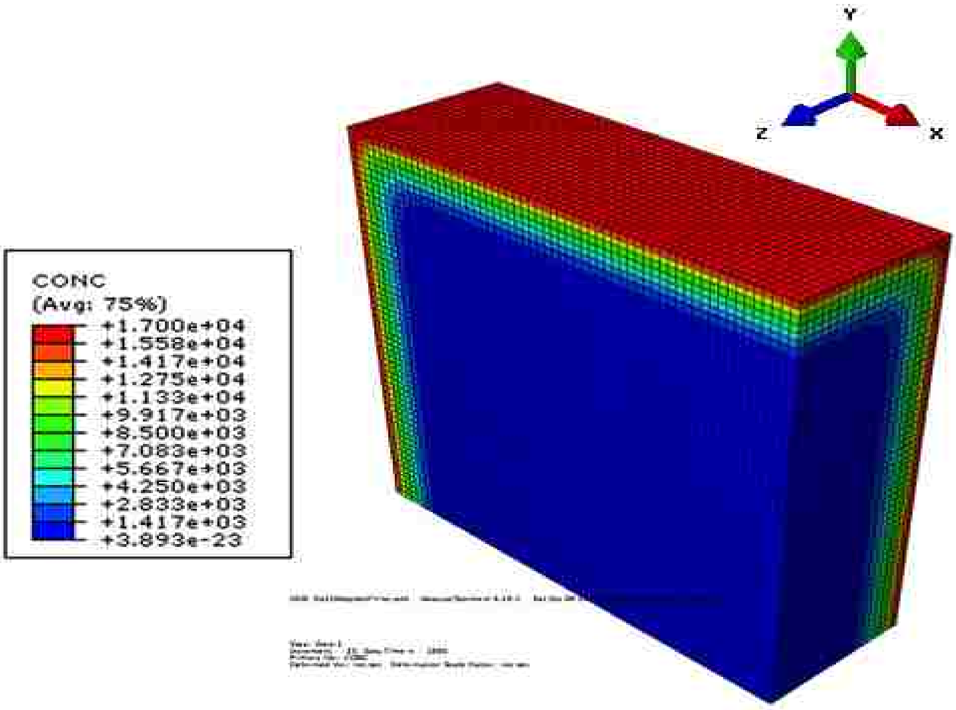

Figure 5.9 Model with Moisture Applied on all External Faces

Figure 5.10 shows the comparison between the ABAQUS model using the modified diffusivity coefficient obtained from the edge effect equation, Equation 11 and the ABAQUS 3D model with moisture conditions applied to the edges. Moisture through the thickness was graphed at several locations through the Y-direction of the part. As can be seen in Figure 5.10 close to the edge where moisture was applied higher moisture content was reported, such as the 2.54 mm location, but further into the part lower moisture contents were reported. Determining how applying moisture to the edge affected the moisture uptake in comparison to using a modified diffusivity coefficient was not clarified because the moisture content for the new analysis changed not only in the Z direction but also in the Y direction. Therefore, another method was used and is demonstrated in Figure 5.11.

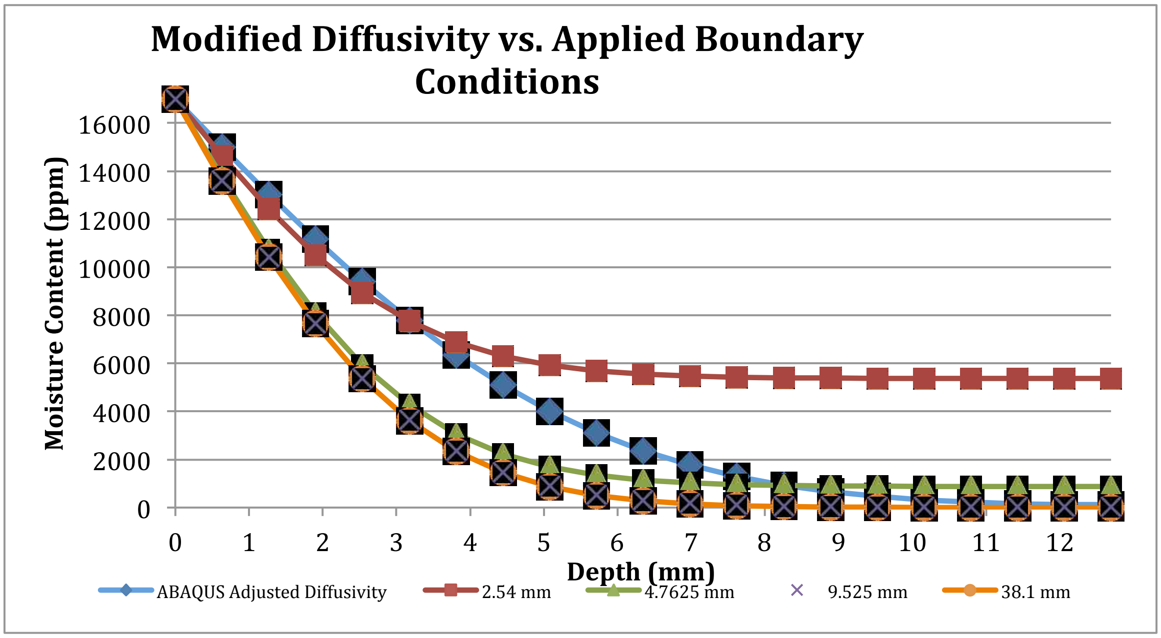

Figure 5.10 Homogeneous Model Comparing Modified Diffusivity and Applied Moisture

In order to better understand the comparison between the results of the output obtained from the ABAQUS model with moisture applied to the edges and the model using the modified diffusivity coefficient, a graph of the average moisture content through the thickness of the part was produced. A single curve of the moisture content through the thickness was created by summing all of the values in the Y-Z plane on the interior surface and then dividing that total by the number of nodes in the Y-direction

Deviation is shown in Figure 5.11. The averaged curve and its comparison to the 1-D method using the edge correction equation indicate a lower uptake near the center of the sample and a higher uptake of moisture near the surface. Varied uptakes most likely can be explained by the fact that the edge effect equation modified the diffusivity coefficient without utilizing a 3D calculation. Even with an averaged curve the relationship between the overall moisture intakes of the two methods was not obvious. Therefore, the overall average moisture content was calculated. The average moisture content through the thickness produced using the modified diffusivity coefficient in one direction was 4622 ppm compared to 3873 ppm for the analysis with moisture boundary conditions applied on all surfaces, meaning the average moisture content through the thickness was 17.63% lower when the moisture boundaries were actually applied. When moisture was applied in only one direction the ABAQUS model was accurate compared to the classic 1D method, but when moisture was applied in all directions ABAQUS deviated from the edge effect equation suggesting that the use of the correcting equation, Equation 11, in non-infinite parts overestimated moisture uptake.

5.3.3. Edge Effect with Applied Boundary Conditions for Orthotropic Model.

Considering that the ultimate goal of this research is the development of accurate and cost effective methods for analyzing hybrid composites, more complex materials were analyzed in the next step. The conditioning time and boundary conditions did not change, but the material properties were modified from homogenous to orthotropic using the values from Table 4.1 for accelerated conditions. Again to obtain a clearer understanding of the difference between using a modified diffusivity coefficient and applying the boundary conditions to the surfaces, the values from the inner faces of the sample were averaged to create a single curve.

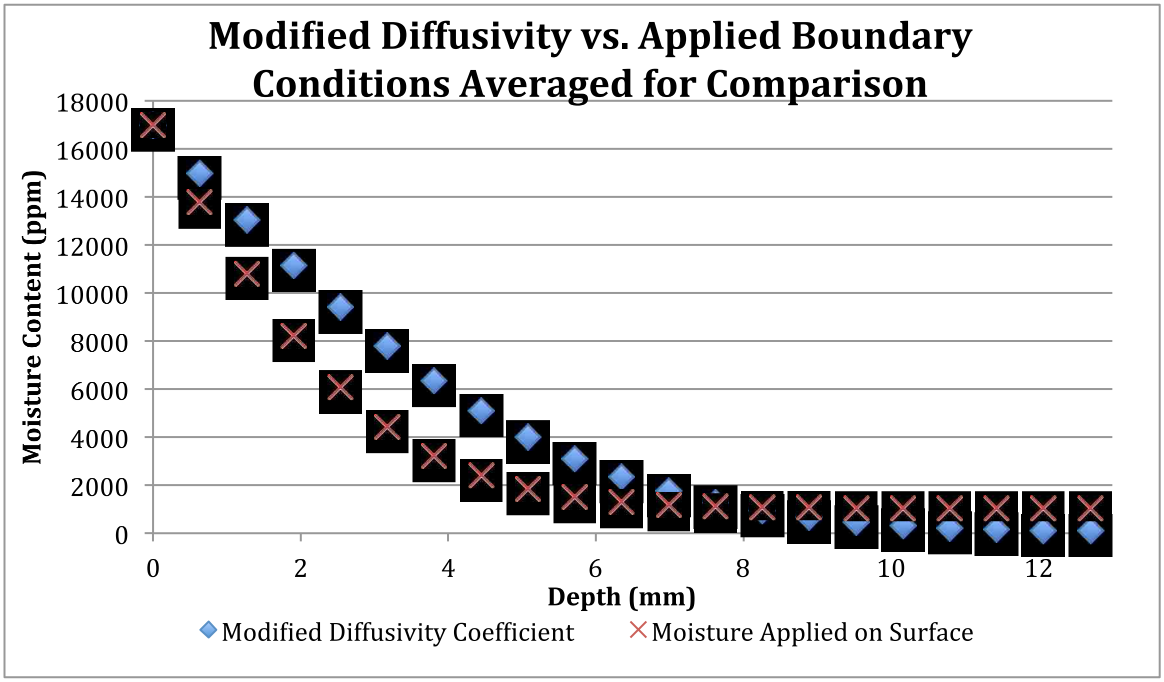

Figure 5.11 Average Moisture Curve for Comparison in Homogeneous Model

The curves displayed in Figure 5.12 indicate that the uptake of moisture in the model with the applied boundary conditions was lower near the part surface and higher near the middle. The average moisture content in the part using the modified diffusivity coefficient was 5106 ppm but the average moisture content from the other method through the Z-direction caused primarily by the D_x diffusivity was only 4082 ppm or 22.28% lower and from the D_y diffusivity was 4050 ppm or 23.13% lower than reported using the edge effect equation. Lower values obtained from the orthotropic materials compared to the homogeneous were consistent and to be expected. Although the previous analysis used the notably higher D_z diffusivity coefficient, allowing for a closer match than the D_x or D_y, the analysis using the D_x or D_y diffusivity coefficients endorsed the previous finding that the traditional calculations overestimate moisture uptake.

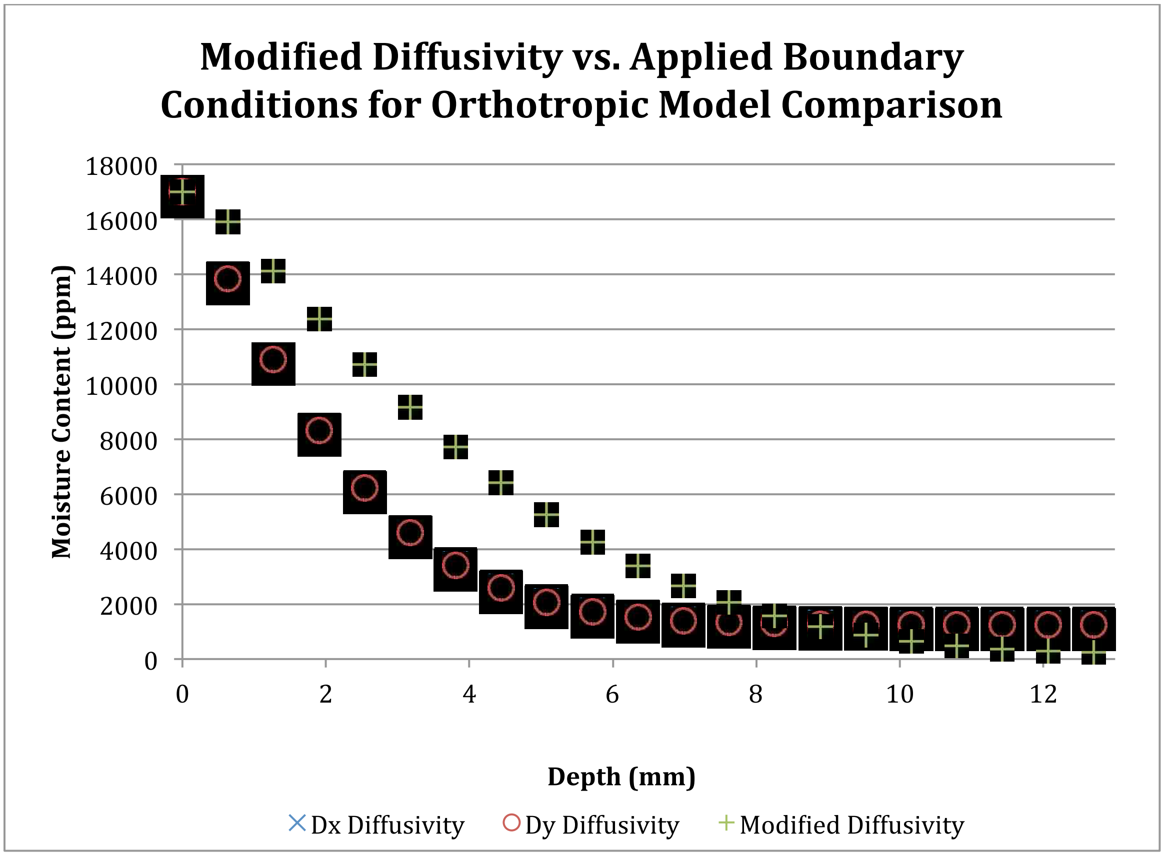

Figure 5.12 Averaged Moisture Curves for Comparison in Orthotropic Model

5.4. REAL WORLD AND ACCELERATED CONDITIONS SOAK TIME

5.4.1. Soak Time to Achieve the Same Average Moisture Content Between Real World and Accelerated Conditions. The first method to determine the required soaking time for a test sample involved calculating a part's average moisture content in the real world and then calculating the length of time required to achieve the same average moisture content using accelerated conditions. The conditions for the sample part included a 1 inch (25.4 mm) thickness, 10 years, 80°F, 82% RH, and an average moisture content calculated using ABAQUS of 2419 ppm. The same model with the accelerated conditions of 160°F and 95% RH was run until the model obtained the same average moisture content as the Design Moisture Content, which according to ABAQUS requires 2036 hours (84.8 days).

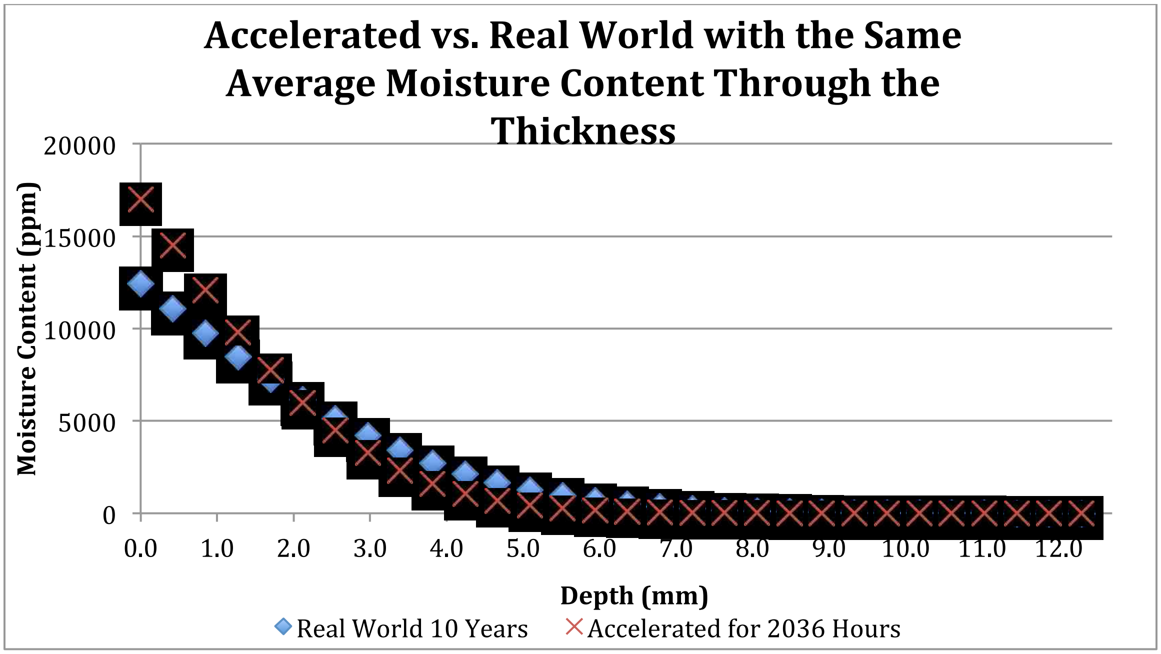

Figure 5.13 Accelerated vs. Real World Same Average Moisture Content

Although, the same average moisture content was obtained, Figure 5.13 indicates the problem of simply running the sample under one set of accelerated conditions. The moisture content that a composite absorbs is directly related to the relative humidity of the environment so the accelerated part becomes over-conditioned near the surface and under-conditioned further into the part. Therefore, a more accurate method of conditioning the sample needs to be implemented.

5.4.2. Accelerated Soak Times That Use Variable Conditions to Ensure Accurate Moisture Through the Sample. In order to obtain samples that under accelerated conditions achieved the same average moisture content while still fitting the moisture content curve of the real world part, an accelerated environment with variable environmental conditions was used. A trial-and-error method was implemented to produce the optimum conditions. Figure 5.13 shows the deviation of the accelerated conditions from the real world moisture content. The accelerated curve was brought into agreement with the real world by monitoring various nodes through the thickness to see if the accelerated conditions resulted in the appropriate moisture content.

Figure 5.14 shows several loading cycles attempting to bring the moisture content at the location 3.81 mm from the edge of the part into accordance with the moisture content from 10 years of soaking. The curve showing real world soaking of 10 years was fitted to Figure 5.14 as a comparison but the time scale did not apply for 10 year curve. A number of cases were run determining the conditions that a part must endure to simulate real world environment. The conditions for each case started with 160°F and 95% RH but the duration of time before the relative humidity was altered to 82% varied. In an effort to decrease total testing time some trials were run with higher temperatures.

Since the material product of composite materials can be altered if placed under extreme temperatures and wanting results that apply generally, the maximum temperature was capped at 200°F. Multiple cases were run to determine the most optimum conditions, but for reasons of simplicity only four representative curves are shown in Figure 5.14 and the conditions are given in Table 5.1.

Table 5.1 Soak Time Parameters for a Number of Variable Accelerated Conditions

Days	Days at 160°F 95% RH	Days at 160°F 82% RH	Days at 200°F 82% RH
147	56	91	-
133	49	84	-
77	42	-	35
73.5	42	-	31.5

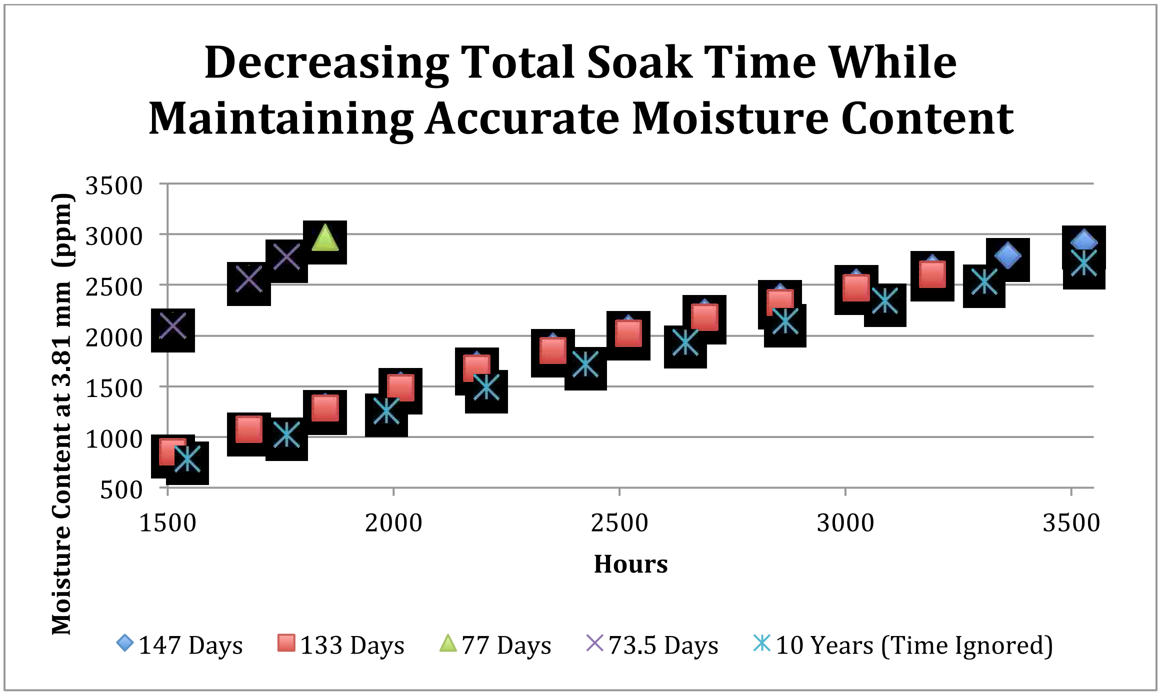

Figure 5.14 Matching Moisture Content at Specific Points Through the Thickness

It was important that the top point of each curve aligned with the last point of the ten years. The value for 133 days (see Figure 5.14) is fairly close. However, since the purpose of the research is to decrease testing time in conjunction with accuracy, the value for 73.5 satisfied both goals producing an acceptable condition in about half the test time.

Observing several locations through the thickness of the model to determine when to alter the environmental conditions was critical to creating an accurate profile for the soaking. Once a specific conditioning cycle created moisture content that matched between the accelerated conditions and the real world at several corresponding nodes, then the average moisture content through the thickness was checked. Figure 5.15 shows the fluctuation of the average moisture content under the different load cycles.

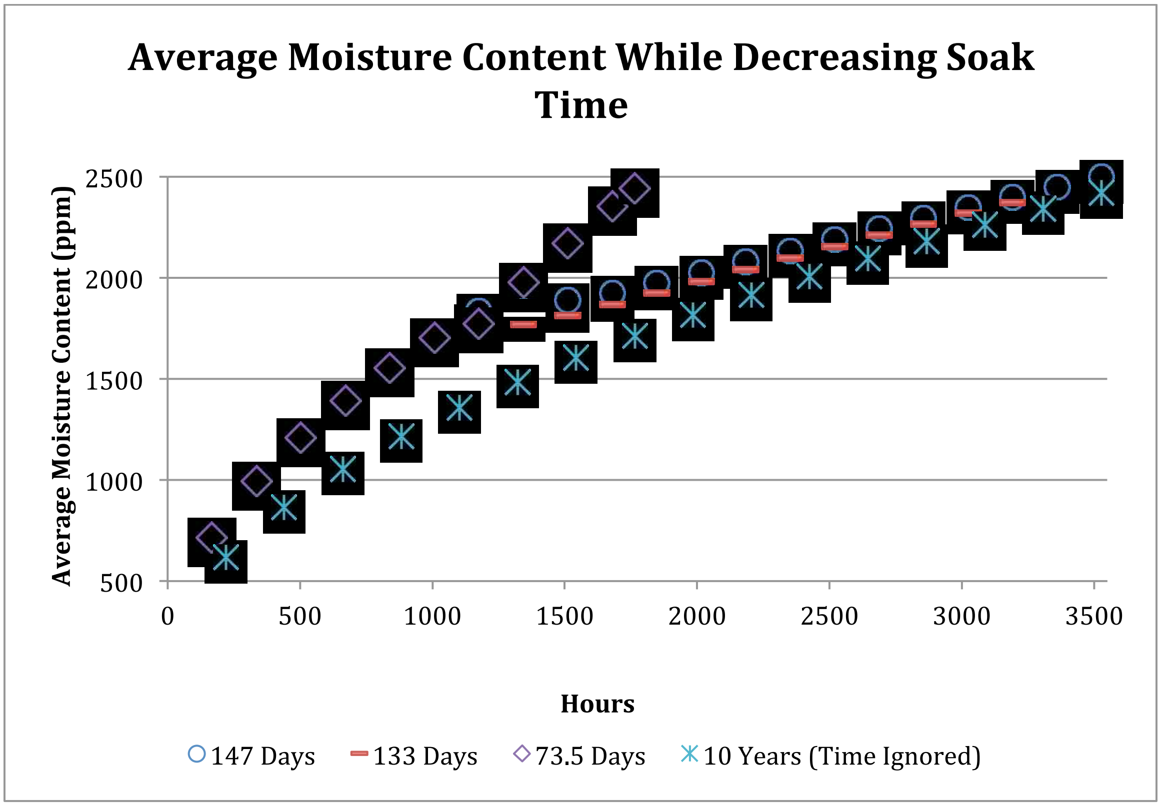

Figure 5.15 Matching Average Moisture Content for Different Conditioning Cycles

As demonstrated in Figure 5.14, the conditions at 133 days created the average moisture content that was very close to the desired real world environment but the 73.5 days case performed just as well in about half the time.

The first analysis, which only took determining average moisture content into account, showed that modeling the sample under the accelerated conditions achieved the same moisture content after 2036 hours (84.8 days) but the curves of the moisture content through the thickness did not agree. Clearly using only one accelerated condition had limitations so using accelerated conditions with varying loads was a better solution. Figures 5.14 and 5.15 show the moisture content matching at least at one node and an equal average moisture content through the thickness of the sample. Figure 5.16 allows for the final check of the data.

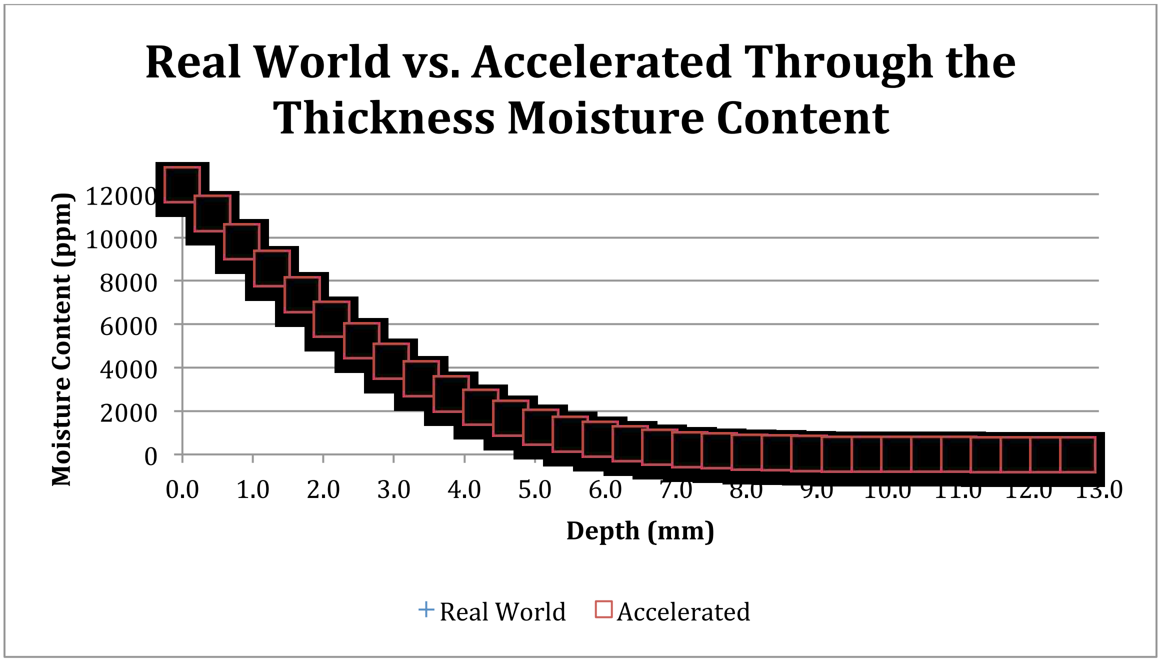

Figure 5.16 Real World vs. Varying Accelerated Conditions

Figure 5.16 shows the moisture content through the thickness comparing the real world conditions of 80°F and 82% RH with the variable accelerated conditions of 42 days at 160°F and 95% RH, and then with 31.5 days at 200°F and 82% RH. The curves agreed with each other. The accelerated environment method created a curve that accurately conditions while at the same time reducing the amount of time the sample needed to remain in the chamber.

6. CONCLUSION

Research at Missouri S&T based upon developing an advanced finite element method determined the appropriate testing time and conditions for composite materials. The research was divided into two stages, the first determined the accuracy of using ABAQUS to analyze moisture diffusion in polymer composite materials and the second to test hybrid composite laminates using the ABAQUS program. The first phase proved the accuracy of ABAQUS by performing a variety of analyses. First, convergence analyses were run using both the Excel and ABAQUS programs. After ensuring the accuracy of the convergence results, a 2D model using diffusion in one direction was compared to the Excel output using the 1D Fick's equation. Results from the 2D model and the Excel output coincided so a 3D model was created that also analyzed diffusion in only one direction to ascertain that no anomalies occurred within the 3D model. Again the results coincided.

Convergence analyses ensured that the ABAQUS model produced accurate results, thus the next stage of analyses was performed. The first set of analyses compared finite and infinite plates. Since the traditional method of calculating moisture diffusion uses a 1D equation, an edge effect equation modifying the diffusivity coefficient was applied so moisture entering from the edges could be taken into account. Rather than modifying the diffusivity coefficient in ABAQUS the model applied moisture boundary conditions to the edges for a true 3D analysis. When completed the average moisture content through the thickness of the sample using ABAQUS was lower in both samples: the homogenous material properties and the orthotropic material properties. The lower average moisture content indicated that the edge effect equation overestimated moisture intake. Furthermore, the traditional method did not give a true profile of the moisture content at different locations in the part. Experimental results need to be acquired for comparison to validate the theoretical results, but given the reliability of the 1D method for moisture diffusion in one direction and capability of ABAQUS to implement the Fick's equation in 3D, assumption of the accuracy of the results seems reasonable.

The last analysis and a large goal of the composite research at Missouri S&T determined the soak time for a test sample that will produce accurate results compared to the real world part without over-conditioning the laminate while at the same time reducing the total testing time in order to save cost. The analysis showed that simply modeling the sample at accelerated conditions until the average moisture content was the same between the accelerated and the real world created a part that was over-soaked near the surface and under-soaked deeper in the part. Certain layers of the lamina were not properly conditioned so cases were run that used an accelerated environment that changed at different times. Findings from the analysis showed that running the part under the increased temperature and relative humidity and then dropping the relative humidity to the real world conditions resulted in a more accurately matched moisture content curve. Fulfilling the additional research objective, that of significantly decreasing testing time, was achieved by changing the relative humidity to the real world condition and raising the temperature in the chamber.

Creating an analysis, which permits environments to change the temperature and relative humidity was rather cumbersome since the moisture equilibrium and diffusivity coefficients must be calculated at all possible conditions. This research assisted in simplifying the calculation process by demonstrating that a subroutine using Equations 9 and 10 with an input of the changing temperature and relative humidity can be written which produces the required calculations.

Missouri S&T in the next phase of the hybrid composite research, which should begin early in 2012, can implement the suggested subroutine in conjunction with other required features for analysis including determining design moisture content after ten years in service, making it possible to control which surface should be exposed to the environment; taking into account interface resistivity of affinity; and allowing for either constant temperature and relative humidity or changing capability of values from a text to simulate the effects of real world conditions. Hybrid composites appear to be the preferred material for many products in the future. Modeling of physical behavior can suggest testing conditions that are accurate, productive, and cost effective for varied industries manufacturing products large and small.

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VITA

Nathan Robert Roe, age twenty-six, has been a resident of Rolla, Missouri since 1989. From August 2003 to 2004, he attended the University of Wyoming in Laramie, Wyoming. January 2005, Roe returned to Rolla to pursue a mechanical engineering degree at the University of Missouri at Rolla (UMR). He was a member of the UMR Formula SAE Team assigned to the body section during his junior and senior years. In this capacity, he became interested in composites and the possibilities in terms of building vehicles.

August 2007, Nathan Roe graduated with honors from UMR with a BSME and a minor in Mathematics and immediately went to work for Polar Tank Trailer, LLC located in Springfield, Missouri as their Research and Development Engineer. His responsibilities included designing and modeling new gasoline tank lines; designing and analyzing bumpers to DOT codes using hand calculations and Finite Element Analysis; and calculating and coding a program in Visual Basic. Professional experience with FEA and interest in composites convinced Roe that he needed to pursue a master's degree in mechanical engineering specializing in those areas. Summer 2009, Roe enrolled at Missouri University of Science and Technology (Missouri S&T) previously known as UMR. He defended his thesis in December 2011 and was awarded the M.S. in Mechanical Engineering from Missouri S&T May 2012.