EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF THE EFFECT OF ENVIRONMENTAL DEGRADATION ON INTERLAMINAR SHEAR STRENGTH OF CARBON/EPOXY COMPOSITES

by

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A THESIS

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ABSTRACT

The effect of environmental and loading conditions on the degradation of Interlaminar Shear Strength (ILSS) of the carbon-epoxy composite specimens was studied in the current research. The hygrothermal conditions capture the synergistic effects of field exposure and extreme temperatures. Short beam shear tests (SBST) were performed to determine the Interlaminar Shear Strength (ILSS) of environmentally aged composite specimens in accordance with ASTM D2344-84. Initially, a standard two-dimensional cohesive layer constitutive model with a cubic traction-separation law was employed in order to simulate the experiment using an in-house Finite Element Analysis code (NOVA-3D). Numerical instabilities encountered using the standard elastic cohesive layer model were overcome by incorporating viscoelastic regularization in the constitutive equations of the cohesive layer. This modification also enabled the analysis to continue beyond the point of peak failure load.

The model was able to accurately simulate the load-deflection behavior of most of the SBST specimens aged under various hygrothermal and synergistically applied stress conditions. Further, the effect of displacement rate on ILSS of specimens was studied using NOVA-3D. A PC based life prediction software, Composite Performance Predictive Tool (CPPT), was developed using a mechanism-based degradation model in order to predict the life of a composite structure under given environmental and loading conditions. The software was benchmarked using the test data.
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>b</td>
<td>Width of Beam</td>
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<tr>
<td>CFRC</td>
<td>Carbon Fiber Reinforced Composite</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>C_{ij}</td>
<td>Cauchy-Green Tensor</td>
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<tr>
<td>CPPT</td>
<td>Composite Performance Prediction Tool</td>
</tr>
<tr>
<td>CPT</td>
<td>Classical Plate Theory</td>
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<tr>
<td>D</td>
<td>Coefficient of Diffusion</td>
</tr>
<tr>
<td>d</td>
<td>Thickness of the specimen</td>
</tr>
<tr>
<td>e</td>
<td>Strain</td>
</tr>
<tr>
<td>DMM</td>
<td>Direct Micromechanical Model</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>F_{ij}(t)</td>
<td>Deformation Gradient in the RVE at Time t</td>
</tr>
<tr>
<td>h</td>
<td>Thickness of Beam</td>
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<tr>
<td>ILSS</td>
<td>Interlaminar Shear Strength</td>
</tr>
<tr>
<td>ISV</td>
<td>Internal State Variable</td>
</tr>
<tr>
<td>L</td>
<td>Length of the specimen</td>
</tr>
<tr>
<td>M_{inf}</td>
<td>Saturation Moisture Uptake</td>
</tr>
<tr>
<td>M(t)</td>
<td>Moisture Uptake after Time t</td>
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<tr>
<td>P</td>
<td>Applied Load</td>
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<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>$P_{\text{max}}$</td>
<td>Failure Load</td>
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<tr>
<td>$r$</td>
<td>Moisture Degradation Parameter</td>
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<tr>
<td>RH</td>
<td>Relative Humidity</td>
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<tr>
<td>RVE</td>
<td>Representative Volume Element</td>
</tr>
<tr>
<td>SBST</td>
<td>Short Beam Shear Test</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Glass Transition Temperature of the Matrix</td>
</tr>
<tr>
<td>UTS</td>
<td>Ultimate Tensile Strength</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>VARTM</td>
<td>Vacuum-Assisted Resin Transfer Molding</td>
</tr>
<tr>
<td>$Z$</td>
<td>Parameter determining the type of crosslink</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Area Fraction in the RVE</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Principal Stretch in the RVE</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>Interlaminar Shear Strength</td>
</tr>
<tr>
<td>${H}$</td>
<td>Hereditary Strain Vector</td>
</tr>
<tr>
<td>$[M(t)]$</td>
<td>Viscoelastic Stiffness Matrix</td>
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CHAPTER 1
INTRODUCTION

Composites offer numerous advantages over conventional structural systems in the form of higher specific stiffness and strength, lower life-cycle costs with additional benefits such as easier installation and improved safety. In recent years, there has been a considerable increase in the use of composites, especially carbon and glass fiber epoxy matrix composites, as appliqués and wraps for seismic upgrading and repairs. However, there is a general lack of data on the long-term performance of these materials which hinders the widespread adoption of these materials. Various factors affect the performance of these composites. Some are related to the fabrication process while others are related to the environmental and loading conditions in real world use. This work focuses on the latter. Since these materials typically fail in a brittle and catastrophic manner with little forewarning, there are heightened concerns related to their capacity for sustained performance under harsh and changing environmental conditions under static and seismic loads.

Current research aims to provide a means for predicting the long-term performance of composite materials, based on laboratory testing and degradation modeling. Accelerated ageing of the specimens was carried out in order to simulate various real world conditions. Loading conditions and mechanical properties of interest included shear, compressive and tensile properties, fatigue, ductility and impact resistance for each type of composite material depending on its application. The current thesis deals particularly with the Interlaminar Shear Strength (ILSS) of carbon-epoxy composites, determined using short beam shear test (SBST).
The various experimental and computational aspects of the current work can be illustrated using Figure 1.

Laboratory experiments, based in Arrhenius principles of accelerated ageing, were conducted to study the degradation of ILSS of carbon-epoxy composite specimens due to the synergistic influence of moisture, applied stress and temperature, viz., hot/wet/unstressed,
cold/wet/unstressed, hot/dry/unstressed, cold/dry/unstressed, hot/wet/stressed, cold/wet/stressed, hot/dry/stressed and cold/dry/stressed.

Experimental results were modeled using a standard elastic two-dimensional cohesive layer constitutive model with a cubic traction separation law. An in-house test-bed FEA code, NOVA-3D, was used for this purpose. One of the problems in modeling the failure of a weak interface using a cohesive-layer is the instability that is encountered due to elastic snap-back. The equations fail to converge at the point of instability due to an imbalance in strain energy. Introduction of a viscosity term in the equations of the cohesive layer helps in overcoming this problem through a “viscous regularization” of the response during unstable crack growth. In the present case, the viscoelasticity based model was able to successfully simulate catastrophic delaminations in short beam shear experiments well beyond peak (failure) load.

The next step was to develop a mechanism based degradation model, which would be the backbone of the life prediction tool. The model incorporated molecular level damages like polymer chain scission due to hydrolysis as well as damages such as, microcracks.

Finally, the life prediction software, Composite Performance Prediction Tool (CPPT), was programmed in Visual Basic. The tool employs a unique combination of the results obtained in the FEA simulations and the degradation model. It is a user friendly tool designed to predict the long-term them performance of carbon-epoxy composites under various environmental and loading conditions. Menu driven parameters entered by the user are used as input by the tool to predict the life of the composite structure as well as its failure mode.
CHAPTER 2
LITERATURE REVIEW

A number of mechanisms are involved in composite degradation. These mechanisms have a wide range of effects on the composites. Interlaminar delamination, fiber-matrix debonding, formation of cracks in the matrix, hydrolysis and erosion of the matrix, fiber slippage and breakage are some of them. Extensive literature is available, documenting various mechanisms of degradation and the agents responsible. Three major categories of degradation agents can be observed, namely environmental, chemical and mechanical. Each category in-turn has various mechanisms. Environmental degradation can be caused by humidity as well as temperature. Similarly, chemical degradation can be caused due to radiation or direct molecular interaction. These various factors can be illustrated using Figure 2.1.

<table>
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<th>AGENTS OF DEGRADATION</th>
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<tr>
<td><strong>ENVIRONMENTAL</strong></td>
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<tr>
<td>Temperature</td>
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<tr>
<td>Sustained</td>
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<td>Hi</td>
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Figure 2.1: Various agents responsible for degradation of composites
It can be seen from the figure that there are a number of agents that can cause degradation. Each of these agents can act independently or in combination with one or more. For example, moisture absorption might lead to some degradation in the composite but moisture, along with another agent like stress or temperature might lead to accelerated degradation. In most real life situations, there is combined action of more than one agent. Hence, it is really important to study the synergistic effect of these agents on the degradation of composites. A number of articles have been published explaining the effect of each of these agents individually. There are a few articles regarding the synergistic effect as well. But there has not been a comprehensive explanation of the mechanism involved in the combined effect of these agents, mainly because of the complexities involved. Understanding the synergistic effect is very important because in real life, many of the above mentioned agents act together and affect the performance and life of the composites. An overview of the available literature is presented in the following pages.

2.1 Influence of Moisture

It has been observed that moisture absorption is one of the most important reasons for degradation of performance of composite materials. Moisture is absorbed from humid environments due to the moisture affinity of some of the functional groups in the resin. Extensive research has been done in order to understand moisture absorption characteristics under various environmental conditions and its effect on the properties of composites.

2.1.1 Moisture Absorption

Moisture absorption data is an important aspect of long-term performance and durability studies of composites. A simple method of evaluating the moisture absorption process in a composite is to obtain the weight-gain data. A plot of weight-gain as a function of time can be
used to understand the influence of moisture. Schematics of various categories of moisture absorption data are illustrated in Figure 2.2 (Weitsman, 2000).

**Figure 2.2: Categories of moisture absorption in polymer composites**

The figure shows the linear Fickian moisture absorption along with various non-Fickian categories. In the figure, the curve for interfacial degradation shows a continuous increase in weight. This is because the water molecules can occupy the deboned volume created by the degraded interface. On contact with the water molecules, the bonds between the resin molecules start breaking and the resin material starts leaching away. This can be observed through the curve for material leaching. The remaining two curves indicate a normal reversible moisture absorption behavior, which is thought to occur due to a competing rate process of water diffusion and polymer relaxation (Zhou, 1999).
Also, moisture absorption has been observed to be dependent on the composite system, fluid, exposure condition and time. For instance, applied stress has been shown to increase the saturation moisture concentration (Weitsman, 2000). Damage due to applied stress and/or moisture diffusion and temperature also plays a major role in composite absorption behavior. A damage mechanics based model was developed by Roy et al. (Roy, 2001) to predict moisture absorption behavior as a function of biaxial (transverse and longitudinal) cracking in a woven textile CFRP composite. While some studies have reported increased diffusion but unchanged saturation concentration (Roy, 2001; Obst, 1996), others reported unchanged diffusion but increased saturation concentration (Patel, 2002). Diffusion and/or saturation concentration have also been observed to be influenced by factors like temperature, fluid acidity, and exposure duration (Weitsman, 2000). All these factors become important in considering the long-term composite durability in hot and humid environments. The effect of polymer viscoelastic relaxation on diffusion was investigated by Roy et al. (Roy, 1987).

A mechanism for degradation in epoxy resins has been discussed by Xiao and Shanahan (Xiao, 1997). The diffused moisture has two phases, a mobile phase and a bound phase. The diffusion of mobile phase is reversible, but the diffusion of bound phase is not. The bound water molecules react with the resin at molecular level and break the crosslink chains. This process of chain scission is called hydrolysis. This breakage of crosslinks weakens the resin over time, thus leading to the degradation of composite properties. By assuming Fickian moisture diffusion and that hydrolysis is the main cause of degradation of the resin, a theoretical model was developed to estimate the remaining number of crosslink after a given time, which can be correlated to degradation of strength and stiffness of the composite.
2.1.2. Influence of Moisture on Static Strength/Stiffness

Unlike glass fibers, which are prone to degradation due to moisture, carbon fibers are largely insensitive to moisture (Weitsman, 2000). Hence, in a carbon fiber based composite, the mechanical behavior of the composite is mainly determined by the matrix and interfacial properties. Formation of residual hygrothermal stresses, polymer and interfacial degradation, and polymer plasticization are some of the possible effects of moisture (Hahn, 1984). A combination of these effects can either enhance or degrade the fracture toughness of the material. Also, the plasticization can result in decreased glass transition temperature (Demonet, 1989) which may strongly affect behavior of the composite in elevated temperature environments.

2.1.3. Effect on Interlaminar Shear Strength

Interfacial strength degradation of carbon/epoxy systems because of water absorption has been reported by Zhuang and Wightman (Zhuang, 1997). The effect of moisture on interfacial shear strength was studied using single fiber fragmentation testing. Specimens were stored in a 100% relative humidity environment at either 23°C or 75°C prior to testing. The results indicated that exposure to humidity caused interfacial shear strength reduction. Specimens were parallel aged at the same temperature in dry conditions and no reduction in strength was observed. This proved that degradation caused only due to the humidity. The reduction in interfacial strength due to humidity exposure was attributed to moisture induced matrix plasticization and subsequent decrease in matrix T_g.

The effect of water absorption on interlaminar shear strength (ILSS) of carbon fiber reinforced epoxy (thermoset) composites (CFRC) and micro or nano sized Al_{2}O_{3} particle dispersed carbon fiber hybrid reinforced composites (CFHRC) was studied by Hussain and Niihara (Hussain, 1999). Different weight change profiles were observed depending on
experimental temperature (55°C and 85°C) and water absorption time. A significant drop in interlaminar shear strength was observed due to epoxy materials degradation, crack development at fiber matrix interfaces by thermal mismatches of matrix and fiber, and/or plasticization of the epoxy matrix. The degree of water absorption of CFRC was controlled by incorporation of nano or micron-sized Al₂O₃ filler into the epoxy matrix. It was observed that the ILSS of CFRC and the micro Al₂O₃ dispersed CFRC was affected at 85 °C. It was also observed that water absorption was significantly higher in micro Al₂O₃ dispersed CFRC compared to nano Al₂O₃ dispersed CFRC. Thus, the degradation of ILSS could be improved by dispersing nano Al₂O₃ instead of micro Al₂O₃.

Hygrothermal effects on the shear properties of carbon-epoxy composites were studied by Botelho et al. (Botelho, 2006). The degradation of composites due to environmental effects is mainly caused by chemical and/or physical damages in the polymer matrix, loss of adhesion at the fiber/matrix interface, and/or reduction of fiber strength and stiffness. The influence of moisture on the shear properties of carbon-epoxy composites laminates of [0/0]s and [0/90]s was studied. The interlaminar shear strength was measured by using the short beam shear test, and Iosipescu shear strength and modulus (G₁₂) was determined by using the Iosipescu test. Results for laminates [0/0]s and [0/90]s, after hygrothermal ageing, showed a reduction of 21% and 18% on the interlaminar shear strength, respectively, when compared to the unaged specimens. Shear modulus also showed a reduction of 14.1% and 17.6% for [0/0]s and [0/90]s, respectively, when compared to the unaged specimens.

Kaelble et al. (Kaelble, 1975) conducted a detailed study of the kinetics of environmental degradation in graphite-epoxy composites. It showed a close correlation between analytical predictions and experimentally observed changes in interlaminar shear and fracture energy
response under high moisture exposure conditions. Unaged composite specimens usually exhibit high interlaminar shear strength and relatively low fracture energy. Exposure to 95% relative humidity or water immersion at 100 °C for greater than or equivalent to 200 hours produced a 30 to 50% reduction in interlaminar shear strength.

The effect of moisture on the tensile and interlaminar shear strengths of glass or carbon fiber reinforced PEI composites was studied by Garcia and Vina (Vina, 2000). Two types of materials were used, PEI reinforced with glass fiber and PEI reinforced with carbon fiber. The materials were exposed to two humid environments, 70°C at 95% relative humidity and immersed in distilled water at room temperature. Exposure times varied from 5 days to 200 days with intervals at 25, 50 and 100 days, after which they were subjected to mechanical testing. The specimens were tested for moisture absorption, tensile strength and interlaminar shear strength. Results showed that the effect of moisture on the strength of the composite occurred during the first 5 days of exposure to moisture. Once the specimens were saturated with moisture, the strengths remained unchanged. It was also noted that temperature did not affect the mechanical properties but acted like an activator of the diffusion of water molecules in the composite. As a result, the specimens absorbed more moisture at a faster rate at higher temperatures so that the material saturated sooner.

Birger et al. (Birger, 1989) studied the failure mechanisms of graphite-fabric reinforced epoxy composites loaded in flexural loading, following ageing in dry, wet and hot environments. Experimental results based on mechanical loading to failure, dynamic mechanical analysis, electron microscopy and infrared spectra indicated that in the case of high temperature ageing in dry conditions the failure mechanism was characterized by shear at short loading spans and by tension at long spans. Interestingly, the failure mode for long spans changed to shear
delamination after long duration hygrothermal ageing. It was also observed that wet environments upto 50°C did not affect the mechanical properties or failure mode compared to the ambient conditions. Ageing in boiling water, however, was found to be detrimental to the epoxy resin, resulting in the leaching of partially reacted components of the epoxy system. This lead to an increase in the void content and a considerable drop in the mechanical properties of the composite.

2.2. Influence of Temperature

It was discussed in the earlier section that carbon fibers are insensitive to moisture. Similarly, carbon fibers are unaffected up to temperatures of 600°C (McLaughlin, 1996). Hence, the effect of temperature on carbon fiber reinforced composites depends on the changes in the matrix and interfacial regions. Also similar to the moisture case, little work is reported in the literature regarding mechanical (as opposed to thermal) fatigue at elevated temperatures.

2.2.1. Influence of Elevated Temperature on Strength and Stiffness

Even though carbon fibers are not affected by temperature changes, degradation in the matrix dominated properties and fiber/matrix interfacial properties can sometimes be responsible for changes in carbon fiber composite strength and is especially important in fatigue.

The microscopic failure processes in three different types of crossply [0, 90n, 0], where (n=4, 8, 12), graphite/epoxy cross-ply composite laminates at room temperature and at 80°C was studied by Takeda and Ogihara (Takeda, 1994). Two types of epoxy resin, a conventional resin and a toughened resin were used with two types of carbon fibers. Experimental results showed that the tensile strength increased with temperature for the thinnest laminate but decreased slightly for the thicker laminates. It was also observed that in the toughened epoxy composite system, the crack density decreased with temperature.
The effect of isothermal aging on interlaminar shear strengths of quasi-isotropic composites laminates were evaluated by Taylor and Lin (Taylor, 2003). Thermoset bismaleimide (IM7/5260) and thermoplastic polyimide (IM7/K3B) were investigated to determine the aging degradation in different matrix materials. Specimens were aged at temperatures of 300°F, 350°F, and 400 °F and ageing time upto 28 months. Isothermal aging for IM7/5260 initially caused increase due to postcuring effects prior to an overall decrease in interlaminar shear strength compared to the unaged baseline specimens. The ILSS decreased for longer aging times, but showed little variation for different temperatures.

The amount of stress transferred from the matrix to the fiber in a composite was studied by Detassis et al. (Detassis, 1995) using fragmentation testing on single-fiber model composites, as a function of temperature. A low T_g epoxy was used with carbon fibers, with and without sizing agents. Experiments indicated a sharp decrease in interfacial shear strength as the test temperature approaches T_g. The interfacial shear strength values of the sized single-fiber composites were generally much higher than that of the de-sized single fiber. Also, the de-sized single fiber composite interfacial shear strength values were very similar to matrix shear strength values.

2.3. Moisture/Temperature Interaction

Various studies examined the effect of the moisture/temperature combination on composite tensile strength and modulus. Results showed by Almen et al. (Almen, 1989) indicated a degradation of composite properties in a variety of carbon fiber reinforced epoxy woven composite under hot/wet environments. While moisture related degradations in tensile strength and stiffness of 0° and 45° carbon/epoxy composites were found to be independent of
temperature by Shen and Springer (Shen, 1977), tensile properties of 90° laminates were significantly affected by moisture and temperature.

A study to determine effects of hygrothermal environments on the strain energy release rates of carbon/epoxy composites was performed by Asp (Asp, 1998). The combined results of the studies point to an ambiguity as to the effects of moisture and temperature on strain energy release rates, implying that each carbon/epoxy system must be examined individually. Tests performed on HTA/6376C composite for dry and wet specimens over the temperature range of -50°C to 100°C indicated that the effect of moisture and temperature on the critical strain energy release rate was different for each mode of failure.

Haque et al. (Haque, 1991) studied the degradation in tensile properties of fiber reinforced polymer composites induced by moisture and temperature. Specimens consisted of Kevlar 49-epoxy, graphite-epoxy, single fiber and Kevlar 49-graphite epoxy hybrid composites. A temperature range of 23°C to 150°C was considered for both wet and dry specimens exposed moisture for up to 200 days. The results indicated that moisture and temperature degraded the tensile strength of hybrid and single fiber composites. Degradation of tensile modulus was found to be dependent on temperature and the effect of moisture depended on the laminate and exposure conditions. It was also noticed that Poisson’s ratio increased with temperature and presence of moisture increased it further.

Degradation in interlaminar shear strength due to synergistic effect of moisture and temperature was studied by Goruganthu et al. (Goruganthu, 2007). Carbon-epoxy specimens were fabricated and aged under dry and wet conditions, at 70°C and 90°C for each moisture condition. Short beam shear test was conducted to determine the ILSS. Though some post curing effect was observed in some dry specimens aged at 90°C, the strength degradation due to
moisture dominated over the post curing effect in case of the wet specimens. This indicated that degradation effect of moisture dominated the strengthening effect of post curing process for a given temperature. The specimens were also subjected to UV radiation but no significant effect due to UV was observed.
CHAPTER 3

EXPERIMENTAL WORK

Carbon-epoxy composite specimens were fabricated, subjected to accelerated environmental ageing and mechanical tests. Two temperatures were selected in order to simulate the real world conditions, while keeping the test matrix tractable. Arrhenius 10° rule was employed to accelerate the ageing process. The specimens were tested to determine the effect of various environmental conditions on ILSS. The experimental data was used in the modeling part. Each of the three main parts of the experimental phase is explained in detail in this chapter.

3.1 Specimen Fabrication

Unidirectional carbon-epoxy composite specimens used in the current research were manufactured using Vacuum Assisted Resin Transfer Molding (VARTM). This process provides high fiber volume ratio, less voids, and has advantages such as room temperature operation. Unidirectional, [0]$_{30}$, composite laminates of 12 in. x 15 in. x 0.2 in. were fabricated.

3.1.1 Materials

The carbon fiber used, HMF CU-160, was supplied by SciArt, Canada. This is a UNIWEB carbon fiber which consists of non-woven sheets of unidirectional carbon fibers, held in position by a fine spider web of polymer fibrils. Dry carbon fiber UNIWEB weighed 3.5 oz. / sq. yd. and was 0.01 in. thick. The resin system used was SC-780, a low viscosity, two-phase
toughened epoxy supplied by Applied Poleramic Inc. The viscosity of the resin was 300cps at 160°F and its cured density was around 1.09 gm./cc. Chemically, SC-780 consists of 60-70% diglycidylether of bisphenol A, 10-20% aliphatic diglycidylether and 10-20% epoxy toughener. The hardener consists of 70-90% aliphatic amine and 10-20% triethylenetetramine. The mixing ratio of resin to hardener was 100 to 22 by weight or 4 to 1 by volume. The glass transition temperature ($T_g$) of the cured resin is 200°F. The resin is specifically designed for Vacuum Assisted Resin Transfer Molding (VARTM) process. The pot life and viscosity have been tailored to allow infusion at 77°F. SC-780 can be cured at room temperature or at elevated temperature to achieve maximum properties. This resin works well in structural and ballistic applications which require damage resistance. Figure 3.1 shows the individual constituents used.

![Figure 3.1: Individual constituents of the laminate, (a) Carbon fiber, (b) Epoxy Resin and Hardener](image)
3.1.2 VARTM Process

An aluminum flat plate was used as the mold to prepare the composite laminates using VARTM. Figure 3.2 shows a schematic of the VARTM setup and Figure 3.3 shows the actual setup.

Figure 3.2: Schematic of VARTM setup

Figure 3.3: Actual VARTM setup
The mold was thoroughly cleaned with acetone and Frekote. A release film was placed on the mold and the dry carbon fiber was carefully placed on it in the desired configuration. A porous release film was placed on the fiber followed by a distribution mesh. The porous release film permits easy removal of the laminate on curing. The distribution mesh was used to channel the resin flow through the length of the fiber. The distribution mesh should be placed approximately 1 in. beyond the end of the carbon fiber. This allows the resin to seep to the bottom layer of the laminate. It was observed that when the distribution mesh extended only to the end of the laminate length, the resin flow on the mesh was fast and it started to flow out through the outlet pipe. This led to wetting of only the top layers of the carbon fibers, while the lower layers remained dry. A spiral tube attached to a clear vinyl tube was placed on the inlet and outlet sides of the setup. The spiral tube was of 0.5 in. inner diameter and the vinyl tube was of 0.25 in. inner diameter. The outlet pipe was connected to a vacuum pump and the inlet pipe was held in a beaker containing the resin-hardener mixture. The entire setup was vacuum-bagged and debulked for 1 hour before resin infusion to release air pockets in the fabric and minimize void content. The resin flow through the laminate was purely under vacuum pressure.

During resin infusion, the temperature was maintained at approximately 80°F to 85°F to optimize the resin flow and to ensure proper wetting of the laminate. Care must be taken to ensure that no air bubbles enter the setup through the inlet pipe. Once the desired quantity of resin has been infused, the inlet pipe was clamped. The resin continued to flow through the laminate under vacuum pressure for approximately 90 minutes at 85°F. Thereafter, the outlet pipe was closed with a crocodile clamp. The entire setup was left for overnight cure in an oven at 85°F. Throughout the process, care must be taken so that no air enters the setup as this may slow down or even stop the resin flow through the laminate.
After curing, the laminate was removed from the mold and kept on a flat plate to post-cure at 160°F for 6 hours. Post cure at this temperature results in approximately 95%-97% of cross-linking. An acid digestion test and C-scan were performed on the laminates to ensure good quality.

3.2 Accelerated Environmental Ageing

The carbon-epoxy laminate was machined into test specimens that were subjected to environmental ageing under various conditions of temperature, humidity and applied stress levels.

3.2.1 Ageing Panel Description

The unidirectional carbon-epoxy laminates were cut into coupons of 5 in. x 1 in. x 0.2 in.. All the coupons were desiccated to remove existing moisture. The coupons were desiccated for around 6 days. Short beam shear test specimens (1 in. x 0.25 in. x 0.2 in.) were cut from one of the desiccated coupons, named Control Specimen (CS01), and were tested (time t=0) to determine the baseline interlaminar shear strength. This value of ILSS was used as the baseline for comparing the effect of ageing. The remaining coupons were subjected to ageing. In case of the stressed specimens, holes were drilled on coupons and they were aged in special constant strain fixture, to be discussed later in the chapter.

3.2.2 Environmental Conditions

Two temperature conditions, termed ‘hot’ (H: 70°C) and ‘cold’ (C: 50°C), were selected for accelerated ageing. Accelerated moisture ageing of the specimens was carried out in environmental chambers at the two temperature conditions. In order to maintain 100% relative humidity (RH), the ‘hot wet’ and ‘cold wet’ specimens were immersed in de-ionized water. Similarly, dry specimens were aged at 70°C for hot conditions and 50°C for cold conditions. In
In the case of stressed specimens, an applied stress equivalent of 5% ultimate tensile strength (UTS) was applied. Depending on the ageing conditions, the specimens were designated as HWS, CWS, HWU, CWU, HDS, CDS, HDU, CDU where,

- H represents ‘hot’ (70 °C)
- C represents ‘cold’ (50 °C)
- W represents ‘wet’ (100% RH)
- D represents ‘dry’ (0% RH)
- S represents ‘stressed’ (5% UTS)
- U represents ‘unstressed’

The designation of the ageing condition is followed by subscripts 1, 2 or 3 representing the ageing times $t_1$, $t_2$ and $t_3$. The number of specimens tested for each ageing condition and the ageing times in parenthesis are shown in Table 3.1.
Table 3.1: Number of Specimens Aged for SBS Test and their Ageing Times

<table>
<thead>
<tr>
<th>Environmental Exposure Condition</th>
<th>Number of Specimens [ageing time (hours)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$t_0$</td>
</tr>
<tr>
<td>HWU</td>
<td>-</td>
</tr>
<tr>
<td>HDU</td>
<td>-</td>
</tr>
<tr>
<td>CWU</td>
<td>-</td>
</tr>
<tr>
<td>CDU</td>
<td>-</td>
</tr>
<tr>
<td>HWS</td>
<td>-</td>
</tr>
<tr>
<td>HDS</td>
<td>-</td>
</tr>
<tr>
<td>CWS</td>
<td>-</td>
</tr>
<tr>
<td>CDS</td>
<td>-</td>
</tr>
</tbody>
</table>

3.2.3 Stress Coupled Exposure Test Fixture

A unique stainless steel test fixture was designed to apply stress on the HWS, CWS, HDS and CDS specimens. Figure 3.4 shows the fixture. The fixture is used to maintain constant strain in the specimens and thus mitigate premature failure of the specimens due to creep rupture.
The motivation for the development of the fixture comes from Phase-1 of this project. Many composite specimens used in that phase failed prematurely due to creep rupture because of the sustained exposure to applied load. This fixture mitigates this problem by providing a simple methodology to eliminate creep during environmental ageing, while enabling the application of a user-specified constant applied strain on the specimen. A specialized fixture is developed to apply loading on samples with the help of a spring on one end of the specimen and a U shaped specimen holder at the other end. In order to maintain constant applied strain, a beam of rectangular cross-section is placed on the top surface of the specimens and connected to the frame with threaded rods. The beam width and thickness are calculated by approximating it to be in three-point bend configuration with the specimen at the bottom surface of the beam and threaded rods at the top.

The test frame comprises of stainless steel bars welded together at the corners. Two springs are used to apply a constant continuous load. Selection of the springs depends on the amount of strain to be applied on the specimens and the deflection of the spring required from
load measurement perspective. The deflection of the spring plays an important role in the design due to constraints on frame size. One end of the spring is fixed using a threaded rod and the other end of the spring is passed through a hole in the test specimen. The specimens have a hole drilled at the other end and are fixed to the frame with a U-shaped specimen holder as shown in the Figure 3.4. The holder is fixed to the frame with a threaded rod and nut. As the nut is turned clockwise the rod travels downwards, thus elongating the specimen and extending the spring.

The nut is turned continuously until the required spring deflection is achieved. The spring deflection is measured using a Vernier caliper. Once the frame is constructed, a steel beam is placed in the gap between the composite sample and the spring hook which passes through the specimen. The function of the beam is to restrain the specimen from further extending due to creep, thereby maintaining constant strain in the specimens thus preventing premature specimen failure. The beam is held in place using threaded rods which are passed through the top frame and locked in place using nuts. The exact beam dimensions are calculated by assuming the beam to be in three-point bend loading with the loading provided by the spring-loaded specimen at the center of the beam and the supports provided by the threaded rods which hold the beam in place.

The criterion for selection of the restraining beam dimensions is as follows: the dimensions of the beam must ensure that the deflection of the beam is less than 1% of specimen elongation under maximum spring load.

The Ultimate Tensile Strength (UTS) of the composite specimens in the transverse direction was determined to be 18 MPa. A load corresponding to 5% UTS, which is calculated to be 26.10 lb. is applied on the specimens through the springs. The test setup is placed in a water bath in case of HWS and CWS ageing conditions and is placed directly in the oven in case of HDS and CDS ageing conditions. The number of specimens aged using the fixture for each
ageing condition is shown in Table 3.2. A total of 12 test coupons (5 in. x 1 in. x 0.2 in.) were aged for more than 5000 hours using the fixture and none of them had a premature failure. This proves the effectiveness of the design.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Layup</th>
<th>Dimensions (in x in x in)</th>
<th>Number of Specimens</th>
<th>Ageing Time Approx. (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS</td>
<td>[0]_{30}</td>
<td>1 × 5 × 0.2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 3.2: Number of SBS Specimens Aged Using the Constant Strain Fixture

3.3 Mechanical Testing

3.3.1 Test Specimen Description

The 1 in. x 5 in. x 0.2 in. coupons which underwent environmental ageing were subsequently cut into short beam shear test specimens of 1 in. x 0.25 in. x 0.2 in. dimensions. The specimens were cut such that the fibers were along the span length of the test specimen. First, the unaged specimens were tested to determine the baseline ILSS and the aged samples were tested after the corresponding ageing times as shown in Table 3.1. The total number of specimens tested for each ageing condition is shown in Table 3.3. It can be clearly seen that a vast array of testing was conducted. Figure 3.5 shows the dimensions of the test specimen.
Table 3.3: Number of Specimens subjected to SBS Test

<table>
<thead>
<tr>
<th>Environmental Exposure Condition</th>
<th>Number of specimens (ageing time - hours)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t₀</td>
<td>t₁</td>
<td>t₂</td>
<td>t₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unaged</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>HWU</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>HDU</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>CWU</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>CDU</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>HWS</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>HDS</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>CWS</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>CDS</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>113</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.5: Dimensions of the SBST specimen (side view)
3.3.2 Test Method

Short beam shear tests (SBST) were performed to determine the Interlaminar Shear Strength (ILSS) of the composite specimens in accordance with ASTM D 2344-84 standard. SBST were performed on both aged and un-aged specimens in order to investigate the effect of various ageing conditions on the strength. ILSS is mostly matrix-dominated and various environmental degradation mechanisms such as moisture, temperature are more active in the matrix materials. Short beam shear specimens of low length-to-thickness ratio (L/h=5) were considered in three-point bend loading to produce horizontal shear failure between the laminas. The rate of crosshead motion was maintained at 0.05 in/min. Figure 3.6 shows the schematic of the test setup and Figure 3.7 shows the actual experimental setup for the short beam shear test.

Figure 3.6: Schematic of the SBST setup
3.3.3 Determination of Interlaminar Shear Strength

Load vs. displacement behavior of each tested specimen was plotted in order to determine the peak load of failure obtained in the experiment. Interlaminar shear strength was then calculated using the below formula

$$\tau_{max} = \frac{0.75 \times P_m}{b \times h}$$

where,

$\tau_{max} =$ maximum interlaminar shear stress

$P_m =$ maximum load observed during the test

$b =$ measured specimen width

$h =$ measured specimen thickness

ILSS of all the unaged and aged specimens was calculated using the above formula and degradation pattern and the responsible environmental factors were identified.
CHAPTER 4
MODEL DEVELOPMENT

Life prediction of composites using accelerated ageing involving a single degradation mechanism can be done using Arrhenius principle. But that method is unreliable when multiple degradation mechanisms are involved. A theoretical approach is required in order to understand the synergistic effect of multiple interacting factors such as moisture, temperature and stress using a single mechanism. The multiple synergistic mechanisms mentioned above involve moisture diffusion influenced by temperature, effects of stress, strain and also effects of wet and dry environments.

A theoretical development for life prediction based on cohesive layer approach has been developed and implemented in a finite element computer based model (NOVA-3D) by Roy et. al. (Roy, 2005). In this thesis, a viscoelastic cohesive layer modeling approach has been used to model the interlaminar shear failure of short beam shear specimens. A detailed discussion is presented in the next section.

4.1 Modeling of Delaminations

Delaminations in composites have been modeled using an interface model by Cui and Wisnom (Cui, 1992). The model employed spring elements to simulate the delaminations. It is a simple model which could handle both singular and non-singular problems and also, it required
no assumption of existing crack. The model was shown to be able to predict the onset and growth of the delamination by applying it to two sample problems.

FEA simulations were performed by Goruganthu et al. (Goruganthu, 2007) using the cohesive layer failure model to gain insight into the interlaminar failure mechanism of the composites after prolonged environmental exposure. The model was able to simulate the experimental load vs. displacement curve till the point of failure, after which, the analysis became unstable due to numerical instabilities. Therefore, the model was able to capture only the linear part of the load vs. displacement curve.

One of the problems in modeling the failure of a weak interface using a cohesive-layer is the instability that is encountered due to elastic snap-back. The equations fail to converge at the point of instability due to an imbalance in strain energy. Introduction of a viscosity term in the equations of the cohesive layer helps in overcoming this problem through a “viscous regularization” of the response during unstable crack growth (Gao, 2004). Efforts have also been made to overcome this instability using an incremental arc-length approach (Riks, 1978). In the present case, the “viscous regularization” approach is more suitable than Riks method because of its simplicity of implementation and numerical robustness. The viscoelasticity based model was implemented in an in-house code (NOVA-3D) and was able to successfully simulate catastrophic delaminations in short beam shear experiments well beyond peak (failure) load, as described in Chapter 6.

4.2 Cohesive Layer Modeling

The in-house NOVA-3D FEA code was used to simulate the short beam shear experiments conducted in the laboratory. Environment-assisted debonding along the interlaminar interface was simulated using a unique cohesive layer debonding model developed by Roy et al.
(Roy, 2006) that is capable of including environmental effects. Based on an approach discussed by Cui and Wisnom (Cui, 1992) and extensively applied by Roy et al. (Roy, 2006), Roy and Wang (Roy, 2005) to model debond, a synergistic cohesive layer model was employed within the framework of finite element analysis (FEA) that effectively combines both stress-based and fracture-mechanics-based modeling for predicting interlaminar shear strength of CFRP. The traction-separation law employed in the FEA is shown in Figure 4.1.

![Figure 4.1: Traction-separation law for SBS modeling](image)

As mentioned previously, numerical instabilities encountered during the short beam shear test (SBST) simulation were overcome using a viscoelastic cohesive layer employing a micromechanics-based traction separation behavior as discussed by Allen and Searcy (Allen, 1999). An incrementalized form of a traction-displacement law was integrated numerically and implemented in the finite element program to predict crack propagation in viscoelastic media. A technique to overcome convergence problems in finite element simulations of crack nucleation
and growth on cohesive interfaces was discussed by Gao and Bower (Gao, 2004). Such simulations are prone to convergence problems due to the occurrence of elastic snap-back instability. The sudden release of strain energy at the time of failure, which causes instability, is dissipated using natural viscoelastic damping. Consequently, the instability encountered at failure initiation with elastic cohesive elements is circumvented, and as an added bonus, it enables tracking the nonlinear load vs. displacement curve well beyond peak load, as shown in Chapter 6.

### 4.3 Multi-axial Viscoelastic Cohesive Layer Derivation Including Damage Evolution

Based on the work reported by Allen et al. (Allen, 1999), the area averaged fibril tractions across the cross-sectional area of the cohesive layer representative volume element (RVE), as shown in Figures 4.2 and 4.3, may be expressed by,

\[
T_i = \frac{1}{A} \int t_i^{\text{fibril}} dA ; \ i=1,2,3
\]  

(1)

where, \(A\) is the cross-sectional area of the RVE, and \(T_i\) is the \(i^{\text{th}}\) rectangular Cartesian component of traction.
Figure 4.2: Opening Crack Containing Cohesive Ligament (Allen, 1999)

Figure 4.3: Reduction of RVE to Cohesive Zone by Area Averaging Fibril Tractions (Allen, 1999)
Assuming uniform traction within each fibril within the RVE, eqn. (1) can be discretized as,

$$T_i = \sum_{k=1}^{N} \frac{A_k(t)}{A} \tau_{i}^{\text{fbril}} ; i=1,2,3$$

(2)

where, $A_k$ represents the cross-sectional area of the $k^{th}$ fibril within the RVE and $N$ is the number of fibrils in the RVE. From continuum mechanics, components of surface traction vector at the mid-plane of each fibril can be related to the components of the Cauchy stress tensor by,

$$\sigma_{ij} n_j = \tau_i$$

(3a)

$$\bar{\sigma}_{ij} n_j = T_i$$

(3b)

where the overbar represents area averaged quantity (average stress) and $n_j$ are the rectangular Cartesian components of the direction cosines at the fibril mid-plane.

Substituting equations 3(a) and 3(b) in (2),

$$\bar{\sigma}_{ij} n_j = \sum_{k=1}^{N} \frac{A_k(t)}{A} \sigma_{ij}^{\text{fbril}} n_j$$

$$\left\{ \bar{\sigma}_{ij} - \sum_{k=1}^{N} \frac{A_k(t)}{A} \sigma_{ij}^{\text{fbril}} \right\} n_j = 0$$

(4)

Since eqn. (4) must hold for any arbitrary orientation of the normal to the fibril mid-plane, therefore,

$$\bar{\sigma}_{ij} = \sum_{k=1}^{N} \frac{A_k(t)}{A} \sigma_{ij}^{\text{fbril}}$$

(5)

Defining a continuum internal damage parameter ‘$\alpha$’ representing the time varying area fraction of the growing voids with respect to the original cross-sectional area of the RVE,

$$\alpha(t) = \frac{A - \sum_{k=1}^{N} A_k(t)}{A}$$

(6)
Consequently, eqn. (5) reduces to,

\[ \bar{\sigma}_{ij} = (1 - \alpha(t)) \sigma_{ij}^{\text{fibril}} \]  

(7)

As described in Roy and Reddy (Roy, 1988), the multi-axial viscoelastic stress-strain law for a polymer fibril may be expressed in matrix notation as,

\[ \{\sigma(t)\}^{\text{fibril}} = [M(t)](\{\epsilon(t)\} - \{H(t)\}) \]  

(8)

where, \([M(t)]\) is a (6x6) matrix of time-dependent viscoelastic stiffness components, \(\{\epsilon(t)\}\) is the vector containing the components of mechanical strains at time \(t\), and \(\{H(t)\}\) contains the hereditary (load history-dependent) strain components. Details regarding the derivation of the \([M]\) matrix and \(\{H\}\) vector from the viscoelastic convolution integral can be found in (Roy, 1998). Combining eqns. (7) and (8) gives the constitutive relationship between viscoelastic stresses and strains within a cohesive RVE at an interlaminar interface, including evolving damage,

\[ \{\bar{\sigma}(t)\} = (1 - \alpha(t))[M(t)](\{\epsilon(t)\} - \{H(t)\}) \]  

(9)

4.3.1 Damage Evolution Law

In the absence of test data regarding the change of fibril diameter as a function of time, a phenomenological damage evolution law is adapted, given by,

\[ \frac{d\alpha}{dt} = \begin{cases} \alpha_0 \bar{\lambda}^m, & \text{if } \dot{\lambda} \geq 0 \text{ and } \alpha < 1 \\ 0, & \text{if } \dot{\lambda} < 0 \text{ and } \alpha < 1 \end{cases} \]  

(10)

where, \(\bar{\lambda}\) is a principal stretch measure within the RVE (refer to eqn. (18) for details), and \(\alpha_0\) and \(m\) are material constants assumed to be independent of environmental conditions.
4.3.2 Determination of Principal stretch

At any point within the RVE, the deformation gradient $F_{ij}(t)$ is given by,

$$F_{ij}(t) = \frac{\partial x_i}{\partial X_j}$$  \hspace{1cm} (11)

where, $x_i$ is the current configuration and $X_j$ is the reference configuration. The right Cauchy-Green tensor $C_{ij}$ is given by (Malvern, 1969),

$$C_{ij} = \frac{\partial x_k}{\partial X_i} \frac{\partial x_k}{\partial X_j}$$  \hspace{1cm} (12)

In matrix notation, eqn. (12) becomes,

$$[C] = [F]^T [F]$$  \hspace{1cm} (13)

Assuming a multiplicative decomposition of the deformation gradient into stretch and a rotation,

$$[F] = [R][U]$$  \hspace{1cm} (14)

Eqn. (13) becomes,

$$[C] = [U]^T [R]^T [R][U] = [U]^T [U] = [U]^2$$  \hspace{1cm} (15)

Therefore, the principal Eigen value of the stretch tensor $[U]$ can be obtained by taking positive square-root of the highest principal Eigen value of $[C],$

$$U_i = \sqrt{C_i} = \lambda_i$$  \hspace{1cm} (16)

4.3.3 Damage Initiation Criterion

Within the cohesive RVE, damage initiation is assumed to occur if a critical value of the von-Mises equivalent stress $\sigma_{M,cr}$ is exceeded (at each element Gauss point),

$$\sqrt{\frac{(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+(\sigma_{xx}-\sigma_{zz})^2+6(\tau_{xy}^2+\tau_{xz}^2+\tau_{yz}^2)}{2}} \geq \sigma_{M,cr}$$  \hspace{1cm} (17)
If eqn. (17) is satisfied then eqn. (10) is invoked such that,

$$\bar{\lambda}(t) = \lambda_i(t) - \lambda_{CR}, \quad \lambda_i(t) \geq \lambda_{CR}$$  \hspace{1cm} (18)

where $\lambda_i(t)$ is the current value of the principal stretch at time $t$, and $\lambda_{CR}$ is the critical value of principal stretch at damage initiation.

The Prony series coefficients for the viscoelastic creep compliance of the resin required as input to the FEA model were obtained from the work of Muliana and Haj-Ali (Haj-Ali, 2003). They developed a micromechanical model to derive the nonlinear viscoelastic response of laminated composites. Glass/epoxy composite specimens of various off-axis angles were used to calibrate their model and the Prony series coefficients were obtained for the epoxy matrix used in their work. The values of various damage parameters used in the current FEA model are listed in Table 4.1.

Table 4.1: Damage parameters used in FEA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>0.032</td>
</tr>
<tr>
<td>$m$</td>
<td>0.750</td>
</tr>
</tbody>
</table>

4.4 Finite Element Mesh

A two dimensional FEA model was used to simulate the SBST experiments. A 2-D mesh was generated as shown in Figure 4.4. The mesh consisted of a total of 3354 elements out of which 234 elements were viscoelastic cohesive elements. The size of the mesh was determined based on a convergence analysis. An analysis was done to study the effect the cohesive layer thickness on the model behavior. It was observed that as long as the aspect ratio of the cohesive elements remains the same, thickness does not affect the behavior of the model significantly.
Three layers of viscoelastic cohesive elements, along the length of the specimen, were used in the mesh to simulate delaminations. The location of the three layers is shown in Figure 4.4 as ‘V’. Figure 4.5 shows a zoomed-in view of the viscoelastic cohesive layers, showing mesh refinement along the interlaminar interfaces.

Figure 4.4: Mesh used for FEA analysis

Figure 4.5: Zoomed-in view of the cohesive layers

4.5 Boundary Conditions

A displacement control approach was followed in order to simulate the experimental conditions using the NOVA-3D model. Displacement was the input parameter with the reaction force as the output. The displacement was incremented per load step to get a displacement rate of
0.05in/min, as used in the experiment. The displacement boundary condition was applied to three nodes at the center of the top layer and average reaction force at those three nodes was calculated to determine the load carried by the beam. A convergence study was conducted on the relation between the load and the number of nodes on which displacement is applied. The cases considered were, 1 center node, 3 center nodes and 5 center nodes at the top layer. Average of reaction forces in the three cases was calculated and plotted. The results are shown in Figure 4.6.

From the figure, it is clear that the optimum number of nodes to apply the displacement was three. Using one node gave higher values of load and five nodes gave lower value as compared to experimental results. Thus, the modeling was done using the 3 nodes approach.
4.6 Material Properties

Manufacturer specified properties of fiber and matrix were used in the modeling. A fiber volume fraction of 0.53 was used in the modeling. The values of various material properties are given in Table 4.2.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity of the fiber</td>
<td>255000 MPa</td>
</tr>
<tr>
<td>Poisson’s Ratio of the fiber</td>
<td>0.33</td>
</tr>
<tr>
<td>Modulus of Elasticity of the matrix</td>
<td>2826.85 MPa</td>
</tr>
<tr>
<td>Poisson’s Ratio of the matrix</td>
<td>0.39</td>
</tr>
<tr>
<td>Fiber volume fraction</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Finite element modeling of various aged as well as unaged cases was carried out, the results of which are discussed in Chapter 6.
5.1 Environmental Ageing

Before being tested, the carbon-epoxy composite specimens were subjected to moisture desiccation and environmental ageing. The results are presented below.

5.1.1 Moisture Desiccation

The 5 in. x 1 in. x 0.2 in. unidirectional carbon-epoxy coupons were placed in a desiccator with silica crystals at 160°F to remove the existing moisture. The coupons were desiccated for around 6 days while taking the weight readings periodically. It was observed that they lost 0.3 % moisture by weight. Figure 5.1 shows the desiccation plots for the short beam shear samples.

Figure 5.1: Desiccation plot for short beam shear samples
5.1.2 Moisture Absorption

The desiccated test coupons were subjected to various environmental conditions as discussed in Chapter 3. The coupons under wet conditions were weighed periodically to determine the moisture gain. Since the dry specimens were kept in an oven, their weight was assumed to be constant. The moisture absorption readings were taken till the specimens were saturated. Figures 5.2-5.5 show the moisture absorption plots of the wet specimens for HWU, CWU, HWS and CWS ageing conditions respectively.

Figure 5.2: Percentage of Moisture uptake vs. Square root of time for HWU specimens

Figure 5.3: Percentage of Moisture uptake vs. Square root of time for CWU specimens
In order to obtain the moisture diffusivity ($D$) and saturation moisture content ($M_{\text{sat}}$), a Fick’s law fit was made for the wet specimens. Figures 5.6-5.9 show the fit obtained for various wet cases. The values of moisture diffusivity and the saturation moisture content are shown in Table 5.1.
Figure 5.6: Fick's Law Fit for HWU specimens

Figure 5.7: Fick's Law Fit for HWS specimens
Table 5.1: Moisture Diffusivity and Saturation Moisture Content from Fick’s law fit

<table>
<thead>
<tr>
<th>Ageing Condition</th>
<th>Diffusivity (10^{-8}) (cm(^2)/s)</th>
<th>(M_{\text{inf}}) (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWU</td>
<td>11.30</td>
<td>0.9306</td>
</tr>
<tr>
<td>CWU</td>
<td>5.65</td>
<td>0.8302</td>
</tr>
<tr>
<td>HWS</td>
<td>10.15</td>
<td>0.8106</td>
</tr>
<tr>
<td>CWS</td>
<td>37.03</td>
<td>0.7505</td>
</tr>
</tbody>
</table>
5.2 Mechanical Testing Results

5.2.1 Control Specimens

Before environmental ageing, one set of desiccated specimens was designated as control specimens (CS01) and was subjected to short beam shear test as explained in Chapter 3. The load vs. displacement behavior of the five tested specimens is shown in Figure 5.10. Table 5.2 shows the interlaminar shear strength ($\tau_{\text{max}}$) data of the specimens. The obtained average ILSS value of 50.42 MPa was used as baseline value to determine the effect of ageing.

![Load vs Displacement for CS01](image)

**Figure 5.10: Load vs. Displacement graphs for control specimens (CS01)**

**Table 5.2: Interlaminar shear strength data for control specimens**

<table>
<thead>
<tr>
<th>Number</th>
<th>Specimen</th>
<th>$\tau_{\text{max}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CS01-1</td>
<td>54.46</td>
</tr>
<tr>
<td>2</td>
<td>CS01-2</td>
<td>49.54</td>
</tr>
<tr>
<td>3</td>
<td>CS01-3</td>
<td>49.22</td>
</tr>
<tr>
<td>4</td>
<td>CS01-4</td>
<td>48.42</td>
</tr>
<tr>
<td>5</td>
<td>CS01-5</td>
<td>50.48</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>50.42</strong></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td></td>
<td><strong>± 2.37</strong></td>
</tr>
</tbody>
</table>
5.2.2 Aged Specimens for time $t_1$

Once the wet specimens were saturated with moisture, as verified by the absorption curves, they were taken out of the environmental chamber and subjected to SBST. The corresponding dry specimens were tested at the same ageing time as their wet counterparts. Load vs. displacement curves were plotted for all the tested specimens and are shown in Figure 5.11. The test data and the change in ILSS for each aging condition are summarized in Table 5.3. It can be observed that the ILSS of the wet samples degraded by around 25%. The degradation in case of the dry samples was less than 10%.
Figure 5.11: Load vs. Displacement plots for SBST of various aged specimen for time $t_1$. 
Table 5.3: Comparison of interlaminar shear strength of various aged samples ($t_1$) with control sample interlaminar shear strength (CS01)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>HWU1</th>
<th>CWU1</th>
<th>HDU1</th>
<th>CDU1</th>
<th>HWS1</th>
<th>CWS1</th>
<th>HDS1</th>
<th>CDS1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ageing time $t_1$ (hours)</td>
<td>1684</td>
<td>1680</td>
<td>1968</td>
<td>1920</td>
<td>1016</td>
<td>1016</td>
<td>1992</td>
<td>1920</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Interlaminar Shear Strength (MPa)</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>CS01</th>
<th>% Change in ILSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37.42 39.81 49.07 47.20 37.73 39.44 53.58 46.55</td>
<td>37.76</td>
<td>±1.08 ±3.04 ±1.54 ±1.75 ±0.26 ±1.20 ±2.00 ±0.96</td>
<td>50.42</td>
<td>-25.10 -27.11 -1.05 -9.63 -25.42 -25.00 9.16 -5.43</td>
</tr>
<tr>
<td>2</td>
<td>38.42 36.66 50.41 46.94 37.78 38.02 54.24 48.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>36.17 37.91 48.30 43.87 37.68 37.00 54.34 48.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>39.02 32.63 51.79 44.22 37.21 36.81 58.00 47.23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.3 Aged Specimens for time $t_2$

These specimens were subjected to a further ageing of another 1500 hours after $t_1$ and then were tested to determine their ILSS. The results of the tests were tabulated as similar to the previous case. Table 5.4 shows the experimental data for ageing time $t_2$. Figure 5.12 shows the
load vs. displacement curves for various specimens. It can be seen that the degradation in ILSS of wet samples is still above 20% and the slight increase in the case of dry samples can be attributed to post curing effect.

Table 5.4: Comparison of Interlaminar shear strength of various aged samples ($t_2$) with control sample interlaminar shear strength (CS01)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Interlaminar Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HWU2</td>
</tr>
<tr>
<td>Ageing time $t_2$ (h)</td>
<td>3378</td>
</tr>
<tr>
<td>Sample Number</td>
<td>Interlaminar Shear Strength (MPa)</td>
</tr>
<tr>
<td>1</td>
<td>35.33</td>
</tr>
<tr>
<td>2</td>
<td>36.79</td>
</tr>
<tr>
<td>3</td>
<td>35.89</td>
</tr>
<tr>
<td>4</td>
<td>38.25</td>
</tr>
<tr>
<td>Average</td>
<td>36.57</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>±1.27</td>
</tr>
<tr>
<td>CS01</td>
<td>50.42</td>
</tr>
<tr>
<td>% change in ILSS</td>
<td>-27.46</td>
</tr>
</tbody>
</table>
Figure 5.12: Load vs. Displacement plots for SBST of various aged specimen for time $t_2$
5.2.4 Aged Specimens for time $t_3$

After ageing time $t_2$ the specimens were further aged for another 1500 hours and subjected to SBST. Figure 5.13 shows the load vs. displacement curves for various specimens. The results are shown in Table 5.5. The ILSS degradation in wet samples was still around 25% and was negligible in case of dry samples. In fact, a slight increase in shear strength was observed in case of dry specimens.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Interlaminar Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37.22 38.90 49.98 47.49 37.68 39.08 55.85 47.90</td>
</tr>
<tr>
<td>2</td>
<td>37.57 36.66 51.40 51.68 38.99 43.07 53.87 48.40</td>
</tr>
<tr>
<td>3</td>
<td>37.55 39.36 52.45 51.91 36.80 37.72 55.82 44.76</td>
</tr>
<tr>
<td>4</td>
<td>39.61 41.44 49.48 51.93 37.47 42.97 49.61 48.79</td>
</tr>
<tr>
<td>Average</td>
<td>37.99 39.09 50.83 50.75 37.74 40.71 53.79 47.46</td>
</tr>
</tbody>
</table>

| Standard Deviation | ±1.09 ±1.96 ±1.35 ±2.17 ±0.92 ±2.72 ±2.93 ±1.83 |
| CS01              | 50.42 50.42 50.42 50.42 50.42 50.42 50.42 50.42 |
| % change in ILSS  | -24.64 -22.46 0.81 0.65 -25.68 -19.25 6.68 -5.87 |

Table 5.5: Comparison of Interlaminar shear strength of various aged samples ($t_3$) with control sample interlaminar shear strength (CS01)
Figure 5.13: Load vs. Displacement plots for SBST of various aged specimen for time $t_3$
5.3 Discussion

Figure 5.14 shows the change in ILSS for each ageing condition with ageing time. It can be observed that the variation in ILLS strength with ageing time occurred till about the 3500 hour mark. Thereafter, the strength remained approximately constant. Another clear observation was that the interlaminar shear strength of the dry specimens was much higher compared to the wet ones after ageing. This clearly established moisture as one of the prime driving force of degradation.

![ILSS v/s Time](image)

**Figure 5.14: Variation of ILSS with time**

The average ILSS of dry specimens after 5000 hours of ageing was 50.70 MPa, which was a 0.55% increase compared to the 50.42 MPa of the control specimens. Hence, in dry case, neither temperature nor stress seemed to affect the strength of the composite. Though there was some variation in between, it balances out by the end. The slight increase in the strength of dry specimens was possibly due to the post-curing effect. In case of wet specimens, the average ILSS after 5000 hours of ageing was 38.88 MPa, a decrease of 22.88% compared to control
specimens. Under wet conditions, temperature did not seem to be driving the degradation. Stress, accompanied by moisture caused the fastest degradation, as seen from the HWS and CWS curves in Figure 5.14. Thus, it was concluded that moisture played a very significant role in the degradation of ILSS. A synergistic combination of moisture and stress caused the fastest rate of ILSS degradation.
6.1 Short Beam Shear Test Modeling Results

The SBST was modeled using NOVA-3D as discussed in Chapter 4. The model was then calibrated to match the experimental load-displacement results as closely as possible. The effect of various environmental conditions was simulated by varying the value of the critical von Mises stress. The analysis was carried out with displacement control. Displacement boundary conditions were applied on the three center nodes of the top layer and the reaction force was calculated. The rate of displacement is same as the one used in actual experiment.

6.1.1 Control Specimens

The value of the critical von Mises stress for the control specimen was obtained using the von Mises stress equation. Assuming a case of pure shear, the von Mises stress is given as,

$$\sigma_{VM} = \sqrt{3}\tau_{xz}$$

The value of shear strength for baseline carbon-epoxy composite was found to be 69 MPa (Jones). Thus, the value of $\sigma^c_{VM} = 119.6$ MPa. The experimental load vs. displacement curve is compared to the one obtained using FEA in Figure 6.1. Figure 6.2 shows the delamination cracks generated in the model and a zoomed-in view of the same is shown in Figure 6.3.
Figure 6.1: Experimental and FEA load vs. displacement curves for control sample for SBST

Figure 6.2: Crack propagation in SBST simulation

Figure 6.3: Zoomed-in view of the delamination in cohesive layer
6.1.2 Aged Specimens

With viscoelastic regularization as explained in Chapter 4, the FEA model was able to match the experimental results for most of the cases with sufficient accuracy. By varying the value of the critical von Mises stress to reflect the influence of hygrothermal ageing, SBST for all the aged specimens was modeled. Note that the FEA model was able to predict peak load as well as simulate the unloading that occurred post-failure. The experimental load vs. displacement curves are shown with the curves obtained in FEA for the three ageing times respectively in Figures 6.4, 6.5 and 6.6.
Figure 6.4: Experimental and FEA load vs. displacement curves for various ageing conditions at time $t_1$ for SBST
Figure 6.5: Experimental and FEA load vs. displacement curves for various ageing conditions at time $t_1$ for SBST
Figure 6.6: Experimental and FEA load vs. displacement curves for various ageing conditions at time $t_1$ for SBST.
The values of critical von Mises stress used in the FEA for various ageing conditions are tabulated in Table 6.1.

**Table 6.1: Values of critical von Mises stress used in FEA for different ageing conditions**

<table>
<thead>
<tr>
<th>Ageing Condition</th>
<th>Critical von Mises Stress (MPa)</th>
<th>Percentage change from baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Specimen</td>
<td>119</td>
<td>0.00</td>
</tr>
<tr>
<td>HWU</td>
<td>63</td>
<td>-47.06</td>
</tr>
<tr>
<td>CWU</td>
<td>64</td>
<td>-46.22</td>
</tr>
<tr>
<td>HWS</td>
<td>50</td>
<td>-57.98</td>
</tr>
<tr>
<td>CWS</td>
<td>70</td>
<td>-41.18</td>
</tr>
<tr>
<td>HDS</td>
<td>123</td>
<td>3.36</td>
</tr>
<tr>
<td>CDS</td>
<td>100</td>
<td>-15.97</td>
</tr>
<tr>
<td>HDU</td>
<td>130</td>
<td>9.24</td>
</tr>
<tr>
<td>CDU</td>
<td>135</td>
<td>13.44</td>
</tr>
</tbody>
</table>

The error in peak load prediction between FEA and experiment for various ageing conditions for the three ageing times is shown in Tables 6.2, 6.3 and 6.4.

**Table 6.2: Error in Peak load prediction for time $t_1$ for SBST simulation**

<table>
<thead>
<tr>
<th>Ageing Condition</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWS</td>
<td>0.46</td>
</tr>
<tr>
<td>CDS</td>
<td>-1.24</td>
</tr>
<tr>
<td>CWS</td>
<td>-0.67</td>
</tr>
<tr>
<td>CWU</td>
<td>-0.66</td>
</tr>
<tr>
<td>HDS</td>
<td>-1.60</td>
</tr>
<tr>
<td>HWU</td>
<td>-0.24</td>
</tr>
<tr>
<td>CDU</td>
<td>-0.76</td>
</tr>
<tr>
<td>HDU</td>
<td>-0.17</td>
</tr>
</tbody>
</table>
### Table 6.3: Error in Peak load prediction for time $t_2$ for SBST simulation

<table>
<thead>
<tr>
<th>Ageing Condition</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWS</td>
<td>0.34</td>
</tr>
<tr>
<td>CDS</td>
<td>-4.38</td>
</tr>
<tr>
<td>CWS</td>
<td>-1.09</td>
</tr>
<tr>
<td>CWU</td>
<td>-1.27</td>
</tr>
<tr>
<td>HDS</td>
<td>-2.76</td>
</tr>
<tr>
<td>HWU</td>
<td>-1.47</td>
</tr>
<tr>
<td>CDU</td>
<td>-0.15</td>
</tr>
<tr>
<td>HDU</td>
<td>-0.64</td>
</tr>
</tbody>
</table>

### Table 6.4: Error in Peak load prediction for time $t_3$ for SBST simulation

<table>
<thead>
<tr>
<th>Ageing Condition</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWS</td>
<td>-1.02</td>
</tr>
<tr>
<td>CDS</td>
<td>-1.39</td>
</tr>
<tr>
<td>CWS</td>
<td>-1.43</td>
</tr>
<tr>
<td>CWU</td>
<td>-1.10</td>
</tr>
<tr>
<td>HDS</td>
<td>-2.00</td>
</tr>
<tr>
<td>HWU</td>
<td>0.00</td>
</tr>
<tr>
<td>CDU</td>
<td>-0.65</td>
</tr>
<tr>
<td>HDU</td>
<td>-0.57</td>
</tr>
</tbody>
</table>

Good agreement is observed, with a maximum error of around 5% in peak load prediction.

### 6.1.3 Influence of Displacement Rate on ILSS

FEA simulations were carried out using NOVA-3D for the SBST experiments by varying the displacement rate. The experimental displacement rate of 0.05 in/min was considered as baseline. The analysis was done at displacement rates of 0.01 in/min and 0.1 in/min while keeping all other parameters constant. The results are shown in Figure 6.7. Not surprisingly, significant rate-dependence in predicted peak load is observed due to the viscoelastic nature of the cohesive layers employed in the FEA analysis.
Figure 6.7: Load vs. displacement plot for various displacement rates

Figure 6.8 shows the predicted stress-strain response for various displacement rates within a cohesive layer element for a particular ageing condition. Similar to Figure 6.7, significant rate-dependence in predicted peak stress is observed due to the viscoelastic nature of the cohesive layers employed in the FEA analysis.
Figure 6.8: Stress vs. strain response for various displacement rates

Figure 6.9 shows the predicted stress vs. strain plot within a cohesive element in the path of the delamination for two ageing conditions (wet and dry). It can be observed that the wet sample has significantly lower strength and lower work of separation (indicated by the area under the curve) compared with the dry case.
6.1.4 Comparison with Elastic Cohesive Layer Model

The results obtained in the current simulation are compared with the results of an earlier analysis using purely elastic cohesive layer, as shown in Figure 6.10. Although the material used and the traction-separation law used was different, the comparison clearly shows the ability of viscoelastic cohesive layer to continue the analysis beyond peak load due to the benign effect of viscous regularization, which was not the case with earlier elastic analysis.
6.2 Discussions

An error of 6.56% was seen in the peak load prediction for control specimen. It was also observed that the model predictions were in good agreement with the experimental results for most of the ageing conditions. Tables 6.2, 6.3 and 6.4 show the error in peak load prediction for ageing condition for the three ageing times respectively. It was noted that the error is less than 5% in all the cases. Interestingly, the error in peak load prediction was consistently less in case of the wet specimens compared to the dry specimens. It showed that the model woks particularly well for the cases where strength degradation due to moisture occurred. It was also seen that the critical von Mises stress varied in a way similar to the variation of ILSS in the experiment for each ageing condition. This again proves the effectiveness of the model. The effect of displacement rate was also observed by performing the analysis at different displacement rates while keeping the remaining parameters constant. As expected, significant rate dependence was observed. Unfortunately, this could not be verified with experiments. From Figure 6.9, it can be observed that the FEA model perfectly captured the degradation of strength. The stress-strain response of the wet specimen indicated a lower work of separation compared to
the dry specimen. Comparison of the viscoelastic cohesive layer model with the elastic cohesive layer model can be seen in Figure 6.10. It can be seen that the elastic cohesive layer model becomes unstable at the point of failure. On the other hand, the viscoelastic cohesive layer model is stable in predicting the load vs. displacement behavior even after failure.
CHAPTER 7

COMPOSITE PERFORMANCE PREDICTION TOOL (CPPT)

7.1 Introduction

The ultimate objective of the research is to develop a Composite Performance Prediction Tool (CPPT). CPPT is a field usable design software that can predict failure load and/or time to failure under given environmental and loading conditions. The software requires the user to input environmental and loading conditions or service time and calculates the maximum load/time to failure. The software has a mechanism-based approach that includes the synergistic effect of environmental (moisture and temperature) and loading conditions on the composite laminate. The software contains a graphical user interface (GUI) to make it user friendly.

7.2 Design Approach

Figure 7.1 shows the flowchart which illustrates the design approach for determining progressive failure.
Figure 7.1: Flowchart depicting the CPPT design methodology

It consists of the following features:

- Use classical plate theory (CPT)
- Allow distributed and concentrated loading
- Allow matrix softening due to moisture using a mechanism-based internal state variable (ISV)
- Transform stresses to micro scale representative volume element (RVE) and calculate strain invariants in fiber, matrix and fiber-matrix interface to include stress amplification
- Degrade laminate stiffness and strengths using ISV and check for failure
- For delamination, calculate $\tau_{xz}$ from cylindrical bending theory and compare with degraded $\sigma_{VM,CR}$
- If failure is detected, check whether it is final failure ($\tau_{xz} > S(t)\tau_{critical}$ (for SBST) or $\varepsilon_x > S(t)\varepsilon_{critical}$ (for flexure))
- If it not final failure, then modify the stiffness in macroscale laminate and increase load
- Stop when final failure is detected

7.3 Solution for a Beam Problem Using Classical Plate Theory

A beam under two loading conditions is considered and the deflections, strains and stresses are calculated using Classical Plate Theory. The salient features of this procedure are:

- The stiffness values are calculated using the following formulae

$$
A_{ij} = \sum_{k=1}^{N} (\bar{Q}_{ij})^{(k)} (z_k - z_{k-1})
$$

$$
B_{ij} = \frac{1}{2} \sum_{k=1}^{N} (\bar{Q}_{ij})^{(k)} (z_k^2 - z_{k-1}^2)
$$

$$
D_{ij} = \frac{1}{3} \sum_{k=1}^{N} (\bar{Q}_{ij})^{(k)} (z_k^3 - z_{k-1}^3)
$$

Hence, the ply orientations are included in the calculations and therefore, the software is not restricted to any particular orientation.

- The laminate is not assumed to be symmetric, which is the case when damage initiates asymmetrically in a layer within a laminate that may be initially symmetric.
7.3.1 Beam with Concentrated Load at the Center

Considering a simply supported beam of unit depth under concentrated loading at the center, as shown in Figure 7.2, we have the following governing equations.

\[ \bar{N}_x = N_x + N_{ht} = A_{11} u_{,x} - B_{11} w_{,xx} \]

Since \( N_x = 0 \),

\[ N_{ht} = A_{11} u_{,x} - B_{11} w_{,xx} \]  \hspace{1cm} (1)

\[ \bar{M}_x = M_x + M_{ht} = B_{11} u_{,x} - D_{11} w_{,xx} \]  \hspace{1cm} (2)

where, \( N_x \) and \( M_x \) are mechanical load and moment

\( N_{ht} \) and \( M_{ht} \) are hygrothermal load and moment

and \( u \) and \( w \) are the displacements in x and z direction respectively

Also, for three point bending,

\[ M_x = \frac{P x}{2} \] \hspace{1cm} for \( 0 < x < \frac{L}{2} \)

\[ M_x = \frac{P (L - x)}{2} \] \hspace{1cm} for \( \frac{L}{2} < x < L \)
From Eqn. (1)

\[ u_{xx} = \frac{(N_{ht} + B_{11}w_{xx})}{A_{11}} \]  

(3)

\[ B_{11}u_{xx} - D_{11}w_{xx} = \frac{Px}{2} + M_{ht} \quad \text{for} \quad 0 < x < \frac{L}{2} \]

\[ B_{11}u_{xx} - D_{11}w_{xx} = \frac{P(L - x)}{2} + M_{ht} \quad \text{for} \quad \frac{L}{2} < x < L \]

For \( 0 < x < \frac{L}{2} \)

\[ B_{11}u_{xx} - D_{11}w_{xx} = \frac{Px}{2} + M_{ht} \]

Substituting Eqn. (3) in Eqn. (2)

\[ w_{xxx} = \frac{\left( \frac{Px}{2} + M_{ht} - \frac{B_{11}N_{ht}}{A_{11}} \right)A_{11}}{(B_{11}^2 - A_{11}D_{11})} \]

defining,

\[ g = M_{ht} - \frac{B_{11}N_{ht}}{A_{11}} \]

and

\[ D = \frac{(B_{11}^2 - A_{11}D_{11})}{A_{11}} \]

And integrating twice,

\[ w = \frac{1}{D} \left[ \frac{Px^3}{12} + g \frac{x^2}{2} \right] + c_1 x + c_2 \]

Similarly for \( \frac{L}{2} < x < L \)

\[ w_{xxx} = \frac{1}{D} \left[ \frac{P(L - x)}{2} + g \right] \]

\[ w = \frac{1}{D} \left[ \frac{P \left( Lx^2 \right)}{2} - \frac{x^3}{6} + g \frac{x^2}{2} \right] + c_3 x + c_4 \]
Simply supported boundary conditions: \( w(0) = 0 \) and \( w(L) = 0 \) and \( w_{,x}\left(\frac{L}{2}\right) = 0 \)

\[
c_1 = -\frac{1}{D}\left[\frac{PL^2}{16} + \frac{gL}{2}\right]
\]

\[
c_3 = -\frac{1}{D}\left[\frac{3PL^2}{16} + \frac{gL}{2}\right]
\]

\[
c_4 = \frac{1}{D}\left[\frac{PL^3}{48}\right]
\]

Hence, for \( 0 < x < \frac{L}{2} \)

\[
w = \frac{1}{D}\left[\frac{Px^3}{12} + \frac{gx^2}{2} - \frac{PL^2 x}{16} - \frac{gL x}{2}\right]
\]

And for \( \frac{L}{2} < x < L \)

\[
w = \frac{1}{D}\left[\frac{PL^2}{2} \left(\frac{Lx^2}{2} - \frac{x^3}{6}\right) + \frac{gx^2}{2} - \frac{3PL^2 x}{16} - \frac{gL x}{2} + \frac{PL^3}{48}\right]
\]

From Eqn. (3),

For \( 0 < x < \frac{L}{2} \)

\[
u_{,x} = \frac{(N_{ht} + B_{11}w_{,xx})}{A_{11}}
\]

Integrating it, we get

\[
u = \frac{N_{ht} x}{A_{11}} + \frac{B_{11}}{A_{11}D}\left(\frac{Px^2}{4} + gx\right) + c_5
\]

Similarly for \( \frac{L}{2} < x < L \)

\[
u = \frac{N_{ht} x}{A_{11}} + \frac{B_{11}}{A_{11}D}\left(\frac{P}{2}(Lx - \frac{x^2}{2}) + gx\right) + c_6
\]

Applying the boundary conditions: \( u(0) = 0 \) and \( u(L) = 0 \), we get

\[c_5 = 0\]
\[
\sigma_{x}^{(k)} = \tilde{\sigma}_{11}^{(k)} \varepsilon_x
\]
\[
\sigma_{y}^{(k)} = \tilde{\sigma}_{12}^{(k)} \varepsilon_x
\]
\[
\tau_{xy}^{(k)} = \tilde{\sigma}_{16}^{(k)} \varepsilon_x
\]
Calculating out of plane stresses using equilibrium equations of theory of elasticity:

For $0 < x < \frac{L}{2}$

$$\frac{\partial \tau_{xz}}{\partial z} = -\frac{\partial \sigma_x}{\partial x}$$

Integrating for $\tau_{xz}$, we get,

$$\tau_{xz} = -\frac{Q^{(k)}_{11} P}{2D} \left( \frac{B_{11} z}{A_{11}} - \frac{z^2}{2} + H_k \right)$$

Similarly, for $\frac{L}{2} < x < L$

$$\tau_{xz} = \frac{Q^{(k)}_{11} P}{2D} \left( \frac{B_{11} z}{A_{11}} - \frac{z^2}{2} + H_k \right)$$

Boundary conditions: $\tau_{xz} = 0$ at $z = 0$ and $z = h$ and $\tau_{xz}^k(z_{k-1}) = \tau_{xz}^{k-1}(z_{k-1})$

Applying the above boundary conditions, $(n+1)$ equations are obtained for $n$ unknowns.

The $n$ unknown constants, $H_1, H_2...H_n$ can be obtained by using a least square technique.

Writing the $(n+1)$ equations in matrix form, we get,

$$AX = b \quad (4)$$

Where, $A$ is the co-efficient matrix of the order $(n+1)$ by $n$

$X$ is the unknown $(n+1)$ vector which contains the constants to be evaluated

$b$ is the known $(n+1)$ vector on the right hand side

The solution for Eqn. $(4)$ is given by,

$$X = (A^T A)^{-1} A^T b \quad (5)$$

and can be obtained computationally using matrix inversion software.
7.3.2 Beam under Distributed Load

Consider a beam of unit width as shown in Figure 7.3. The distributed load $P$ given by,

$$ P = P(x) = \frac{16P_0}{\pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \sin\left(\frac{m\pi x}{L}\right) $$

The governing equations can be written as,

$$ A_{11}u_{xxx} - B_{11}w_{xxx} = 0 \quad (6) $$

$$ D_{11}w_{xxxx} - B_{11}u_{xxx} = P \quad (7) $$

From Eqns. (6) and (7),

$$ u_{xxx} = \frac{B_{11}}{A_{11}} w_{xxx} $$

Or,

$$ w_{xxxx} = \frac{A_{11}}{D} P $$

Where,

$$ D = A_{11}D_{11} - B_{11}^2 $$

Giving,
\[ w_{xxxx} = \frac{A_{11}}{D} \frac{16P_0}{\pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \sin \left( \frac{m \pi x}{L} \right) \]

Integrating four times,

\[ w = \frac{16A_{11}P_0}{D \pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \left( \frac{L}{m \pi} \right)^4 \sin \left( \frac{m \pi x}{L} \right) + \frac{c_1 x^3}{6} + \frac{c_2 x^2}{2} + c_3 x + c_4 \]

Applying simply supported boundary conditions,

\[ w(0) = 0, w(L) = 0, w_x \left( \frac{L}{2} \right) = 0 \text{ and } w_{xx}(0) = w_{xx}(L) \]

Gives,

\[ c_4 = 0 \]

\[ \frac{c_1 L^3}{6} + \frac{c_2 L^2}{2} + c_3 L = 0 \]

\[ \frac{c_1 L^2}{8} + \frac{c_2 L}{2} + c_3 = 0 \]

\[ \frac{c_1 L^2}{8} + c_2 L = \frac{32A_{11}P_0}{D \pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \left( \frac{L}{m \pi} \right)^3 \]

Solving the above equations,

\[ c_1 = 0 \]

\[ c_2 = \frac{32A_{11}P_0}{LD \pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m \pi} \left( \frac{L}{m \pi} \right)^3 \]

\[ c_3 = -\frac{16A_{11}P_0}{D \pi^2} \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \left( \frac{L}{m \pi} \right)^3 \]

Hence,

\[ w = \frac{16A_{11}P_0}{D \pi^2} \left[ \sum_{m=1,3,5...}^{\infty} \frac{1}{m} \left( \frac{L}{m \pi} \right)^3 \left\{ \left( \frac{L}{m \pi} \right) \sin \left( \frac{m \pi x}{L} \right) + x^2 - x \right\} \right] \]
and

\[ u_{xx} = \frac{B_{11}}{A_{11}} w_{xxx} \]

Integrating twice,

\[ u = \frac{16B_{11}P_0}{D\pi^2} \left[ \frac{1}{m} \left( \frac{L}{m\pi} \right)^3 \cos \left( \frac{m\pi x}{L} \right) \right] + c_1 x + c_2 \]

\[ u = \frac{16B_{11}P_0}{D\pi^2} + \left[ \sum_{m=1,3,5,\ldots}^{\infty} \frac{1}{m} \left( \frac{L}{m\pi} \right)^3 \left\{ \cos \left( \frac{m\pi x}{L} \right) + \frac{2x}{L} - 1 \right\} \right] \]

Evaluating the axial strain,

\[ \epsilon_x = \frac{\partial u}{\partial x} - z \frac{\partial^2 w}{\partial x^2} \]

\[ \epsilon_x = \frac{16P_0}{D\pi^2} \left[ (A_{11}z - B_{11}) \sum_{m=1,3,5,\ldots}^{\infty} \frac{1}{m} \left( \frac{L}{m\pi} \right)^2 \sin \left( \frac{m\pi x}{L} \right) + (2A_{11}z + \frac{2B_{11}}{L}) \sum_{m=1,3,5,\ldots}^{\infty} \frac{1}{m} \left( \frac{L}{m\pi} \right)^3 \right] \]

Stresses in each layer are given by,

\[ \sigma_x^{(k)} = \bar{\sigma}_{11}^{(k)} \epsilon_x \]

\[ \sigma_y^{(k)} = \bar{\sigma}_{12}^{(k)} \epsilon_x \]

\[ \tau_{xy}^{(k)} = \bar{\sigma}_{16}^{(k)} \epsilon_x \]

As derived in previous section, out of plane shear stress is calculated using equilibrium equations given by,

\[ \frac{\partial \tau_{xz}}{\partial z} = -\frac{\partial \sigma_x}{\partial x} \]

or

\[ \tau_{xz} = -\frac{16P_0}{D\pi^2} \left( \sum_{m=1,3,5,\ldots}^{\infty} \frac{1}{m} \left( \frac{L}{m\pi} \right) \cos \left( \frac{m\pi x}{L} \right) \right) \left( \frac{A_{11}z^2}{2} - B_{11}z + H_k \right) \]
Boundary conditions for this case are \( \tau_{xz} = 0 \) at \( z = 0 \) and \( z = n \) and

\[
\tau_{xz}^k(z_{k-1}) = \tau_{xz}^{k-1}(z_{k-1})
\]

Substituting the boundary conditions and writing in a matrix form results in a matrix equation similar to Eqn. (4) whose solution is given by Eqn. (5).

### 7.4 Direct Micromechanical Model for 3-D Local Strains from 2-D Global Strains

In order to incorporate the stress amplification due to the presence of micro-scale inhomogeneities, a finite element analysis based micromechanics method called Direct Micromechanical Model (DMM) was developed to investigate development of micro-cracks in a carbon/epoxy laminate. The unit cell of the composite is modeled using three-dimensional finite elements. Periodic boundary conditions are applied to the boundaries of the unit cell. The stresses in the fiber and matrix phases and along the fiber–matrix interface are calculated. When the laminated composite structure is subjected to combined thermal and mechanical loads, the macro-strains are computed from the global analysis. Then, the macro-strains are applied to the unit hexagonal cell model to evaluate micro-stresses, which are used to predict the formation of micro-cracks in the matrix.

The microscopic image of a uniaxial fiber-reinforced laminate (Figure 7.4) shows that the fiber arrangement is quite random in reality. However, for analytical/numerical modeling, it is convenient to assume some repetitive pattern of fiber arrangement. The hexagonal packing of unit cell, as shown in Figure 7.5 is used to model the RVE as it is closer to reality than square packing pattern, especially when the composite is fabricated with high fiber volume fraction. Theoretically, one can obtain a maximum fiber volume fraction of 91% with hexagonal RVE.
Periodic boundary condition is used for the hexagonal unit cell. The periodic boundary conditions ensure displacement compatibility and stress continuity on the opposite faces of the unit cell.

### 7.4.1 Boundary Conditions of Hexagonal Unit Cell

The unit cells are subjected to axial and shear displacements using periodic boundary conditions. The periodic boundary conditions maintain equal boundary displacements with the adjacent unit cells to satisfy the compatibility of displacements on opposite faces of the unit cell and enforce the continuity of stresses. The hexagonal unit cell is subjected to different strain components individually using the periodic boundary conditions shown in Table 7.1. The equations of periodic boundary conditions corresponding individual unit strains are applied in ABAQUS to perform the FE analysis.
Table 7.1 Periodic boundary conditions for the hexagonal unit cell for the application of unit magnitude of various strain components

<table>
<thead>
<tr>
<th>$\varepsilon_x=1$</th>
<th>$\varepsilon_y=1$</th>
<th>$\varepsilon_z=1$</th>
<th>$\gamma_{xy}=1$</th>
<th>$\gamma_{xz}=1$</th>
<th>$\gamma_{yz}=1$</th>
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<tr>
<td>$u_{a1}-u_{a0}=\sqrt{3}L/2$</td>
<td>$u_{a1}-u_{a0}=0$</td>
<td>$u_{a1}-u_{a0}=0$</td>
<td>$u_{a1}-u_{a0}=0$</td>
<td>$u_{c1}-u_{c0}=0$</td>
<td>$v_{c1}-v_{c0}=0$</td>
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<tr>
<td>$u_{b1}-u_{b0}=\sqrt{3}L/2$</td>
<td>$u_{b1}-u_{b0}=0$</td>
<td>$u_{b1}-u_{b0}=0$</td>
<td>$u_{b1}-u_{b0}=0$</td>
<td>$u_{c1}=0$</td>
<td>$w_{c1}=L/2$</td>
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<td>$w_{a1}-w_{a0}=L/2$</td>
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<tr>
<td>$v_{b1}-v_{b0}=0$</td>
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<td>$w_{a1}-w_{a0}=L/2$</td>
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<td>$v_{c1}=0$</td>
<td>$v_{c1}=0$</td>
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<td>$w_{a0}-w_{b0}=L/2$</td>
</tr>
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<td>$v_{c0}=-L/2$</td>
<td>$v_{c0}=0$</td>
<td>$v_{b1}-v_{b0}=-\sqrt{3}L/2$</td>
<td>$w_{a1}-w_{a0}=\sqrt{3}L/2$</td>
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<td>$w_{c1}-w_{c0}=t$</td>
<td>$w_{c1}-w_{c0}=t$</td>
<td>$w_{c1}-w_{c0}=\sqrt{3}L/2$</td>
</tr>
</tbody>
</table>

Local 3-D strains at three critical points 1, 2 and 3 (Figure 7.6) were detected using periodic boundary conditions applied on hexagon RVE. Transformation matrix obtained using periodic boundary condition at the three locations 1, 2, and 3 are shown in Table 7.2.
<table>
<thead>
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<th>Point 1</th>
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<td>0.0264</td>
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<td>0.3616</td>
<td>0.1292</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e_{33}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>0.3306</td>
<td>0.0002</td>
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<td>0</td>
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<tr>
<td>$e_{33}$</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
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<th>$e_{yy}=1$</th>
<th>$e_{zz}=1$</th>
<th>$e_{xy}=1$</th>
<th>$e_{xz}=1$</th>
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</tr>
</thead>
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<td>-0.0334</td>
<td>0.3650</td>
<td>0.0176</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e_{22}$</td>
<td>-0.0080</td>
<td>0.0265</td>
<td>0.3336</td>
<td>0.0110</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e_{33}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e_{12}$</td>
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<td>0.0673</td>
<td>0.0154</td>
<td>0.2304</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$e_{13}$</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1028</td>
<td>0.0159</td>
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<tr>
<td>$e_{23}$</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0044</td>
<td>0.0133</td>
</tr>
</tbody>
</table>

7.5 Hydrolysis of Epoxy Resins

7.5.1 Epoxy Structure

Epoxy is a copolymer, i.e. it is formed from two different chemicals, a resin and a hardener. The types of resin and hardener used in this research have been discussed in Chapter 3. Resins are usually monomers with an epoxide group at either ends. Most epoxy resins are generated from a reaction between epichlorohydrin and bisphenol-A. Hardeners are usually monomers of polyamine. Triethylenetetramine is an example of a hardener. Figures 7.7 and 7.8
show the chemical structure of a typical resin and hardener. When the resin and the hardener are mixed together, the amine groups in the hardener react with the epoxide groups in the polymer and form strong covalent bonds. This process is called curing. As a result of curing, the resultant polymer is heavily crosslinked and hence, very strong and stiff. The time taken for curing depends on the resin and hardener combination and also the environmental conditions. Also, curing at a higher temperature usually increases the degree of crosslinking.

![Figure 7.7: Resin used to produce epoxy](image)

![Figure 7.8: Hardener with the amine groups](image)

### 7.5.2 Hydrolysis Process

As discussed in the earlier section, epoxy gets its strength and stiffness because of the strong crosslinks produced by the hardener between the polymer monomers. Hydrolysis can be defined as a chemical reaction in which a molecule is split into two parts by the addition of a water molecule. The water molecule splits into a hydrogen ion (H\(^+\)) and a hydroxyl group (OH\(^-\)). These two groups react with the two parts of the broken molecule to generate new compounds. Epoxies are prone to moisture absorption. When exposed to humid conditions, epoxies absorb the water molecules until the resin system is saturated with moisture. A part of the total absorbed
moisture reacts with the crosslinks in the epoxy system causing chain scission (Xiao, 1997). The water molecules act on the amine groups that connect the resin monomers and break the crosslinks. The hydrolysis reaction of an amide molecule is shown in Figure 7.9.

![Figure 7.9: Hydrolysis of an amide molecule](image)

As the crosslinks between the polymer monomers break, the epoxy loses its strength and stiffness. This leads to degradation of the strength and stiffness of the composite laminate. A detailed discussion of this degradation mechanism is discussed in the following sections.

### 7.6 Mechanism-based Modeling of Degradation due to Hygrothermal Aging in an Epoxy Polymer

For one dimensional (through laminate thickness) diffusion case, molecular concentration as a function of space and time is given by (Xiao, 1997),

$$
\frac{\partial m_1}{\partial t} + \frac{\partial m_2}{\partial t} = D \frac{\partial^2 m_1}{\partial x^2}
$$

where, $m_1$ is the number of moles of mobile water per unit volume of the polymer,

$m_2$ is the number of moles of reacted water per unit volume of the polymer,

and $D$ is the moisture diffusivity of the laminate in the through thickness direction.

It is assumed that,

$$
m_2 = r(m_1)
$$

where, $r$ is assumed to be a constant.
7.6.1 Calculation of Moisture Degradation Parameter ‘r’

From moisture absorption and desorption experiments,

\[ m_{1\infty} + m_{2\infty} = 1.33403\% \]

\[ m_{2\infty} = 0.15760\% \]

\[ \frac{m_{2\infty}}{m_{1\infty} + m_{2\infty}} = \frac{0.1576}{1.33403} = 0.11814 = \gamma \]

\[ m_{2\infty} = r(m_{1\infty}) \Rightarrow \frac{r}{1 + r} = \gamma \]

\[ r = 0.13396 \]

7.6.2 Derivation of Internal State Variable (ISV) for Moisture induced Degradation

Defining,

\[ D' = \frac{D}{1 + r} \]

\[ m_{1\infty} = \frac{M_{\infty} \rho_{polymer}}{(1 + r)m_w} \]

where, \( \rho_{polymer} \) is the density of the polymer resin. The solution to Eqn. (8) for total moisture uptake in terms of moles per unit surface area of the laminate is given by

For \( t \leq \frac{0.05d^2}{D'} \)

\[ M_2(t) = \frac{4rm_{1\infty}}{d} \left( \frac{D_m'}{\pi t} \right)^{1/2} \]

For \( t > \frac{0.05d^2}{D'} \)

\[ M_2(t) = rm_{1\infty} \left[ 1 - \frac{8}{\pi^2} e^{-\left( \frac{D_m' \pi^2 t}{d^2} \right)} \right] \]

where, \( d \) is the transverse thickness of the laminate.
If $m_2(t)$ moles of water reacted with the polymer at a given time $t$, then there are $m_2(t)N_A$ bonds broken, where, $N_A$ is Avogadro’s number. The probability of a chain segment being cut $Y$ times is given by (Xiao, 1997),

$$
P\{m_2(t)N_A, Y\} = \left( \frac{1}{N_A N_0} \right)^Y \left( 1 - \frac{1}{N_A N_0} \right)^{(m_2(t)N_A - Y)} \left( \frac{(m_2(t)N_A)!}{Y! (m_2(t)N_A - Y)!} \right) \tag{9}$$

Since $\frac{1}{N_A N_0}$ is very small compared to $m_2(t)N_A$, Eqn. (9) can be written as,

$$
P\{m_2(t)N_A, Y\} = \left( \frac{m_2(t)}{N_0} \right)^Y \exp\left( - \frac{m_2(t)}{N_0} \right) \frac{1}{Y!}$$

If $P(0)$ is the probability of no bond breakage, then the probability of at least one bond breakage is given by,

$$
P(Y \geq 1) = 1 - P(0)$$

$$
P(Y \geq 1) = 1 - \exp\left( - \frac{m_2(t)}{N_0} \right)$$

Assuming $m_2(t) = \frac{M_2(t)}{d}$, where $d$ is the laminate thickness, the number of moles of intercrosslink chains having been cut per unit volume at time $t$ is,

$$
R = N_0 \left[ 1 - \exp\left( - \frac{M_2(t)}{dN_0} \right) \right] \tag{10}
$$

Hence, the remaining number of moles of intercrosslink chains will be,

$$
N(t) = N_0 - ZR \tag{11}
$$

Where, $Z$ is constant and has a value of $1<Z<3$, depending on the crosslink morphology.

Substituting Eqn. (10) in Eqn. (11),

$$
N(t) = N_0 [Z \exp\left( - \frac{M_2(t)}{dN_0} \right) - (Z - 1)]
$$

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$$S_H(t) = \frac{N(t)}{N_0} = Z e^{-\frac{M_2(t)}{dN_0}} - (Z - 1)$$

where, \( N_0 \) = Initial number of network crosslinks per mole at time, \( t=0 \)

\( N(t) \) = Number of remaining network crosslinks per mole at any time, \( t \)

\( Z \) = Parameter determining the type of crosslink (1<\( Z <3 \))

\( S_H(t) \) = mechanism-based ISV quantifying change in crosslink density due to hygrothermal aging

### 7.7 Mechanism-based Modeling of Degradation due to Thermal Degradation in an Epoxy Polymer

Fick’s law of diffusion of oxygen in a polymer composite system incorporating a consumptive reaction with rate \( R(C) \) is given by,

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( D_{11} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{22} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{33} \frac{\partial C}{\partial z} \right) - R(C) \quad (12)$$

where, \( D_{11}, D_{22} \) and \( D_{33} \) are the diffusivities of oxygen in x, y and z directions respectively.

As a first order approximation, assuming that reaction rate \( R(C) \) is proportional to the rate of change of oxygen concentration,

$$R(C) = r \frac{\partial C}{\partial t} \quad (13)$$

where, \( r \) is a proportionality constant.

Substituting (13) in (12),

$$\frac{\partial C}{\partial t} + r \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( D_{11} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{22} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{33} \frac{\partial C}{\partial z} \right)$$

Or,

$$(1 + r) \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left( D_{11} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{22} \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{33} \frac{\partial C}{\partial z} \right) \quad (14)$$
Defining,

\[ D'_{ij} = \frac{D_{ij}}{1 + r} \]

The solution to Eqn. (14) for oxygen uptake in the presence of oxidative reaction assuming one dimensional (through thickness) diffusion is given by,

\[ M(t)_{O_2} = m \omega \left\{ 1 - \frac{8}{\pi^2} \sum_{j=0}^{\infty} \frac{1}{(2j + 1)^2} e^{\left[ \frac{\sigma_{ij}^2 (2j + 1)^2 \pi^2 t}{d^3} \right]} \right\} \]

Where, \( d \) is the transverse thickness of the laminate.

The internal state variable for thermal degradation is obtained in a way similar to the one derived for moisture induced degradation in epoxy in the previous section. It is given by,

\[ S_I(t) = N(t) \frac{N_0}{N_0} = Z e^{-\left( \frac{M(t)_{O_2}}{dN_0^2} \right)} - (Z - 1) \]

where, \( N_0 \) = Initial number of network crosslinks per mole at time, \( t=0 \)

\( N(t) \) = Number of remaining network crosslinks per mole at any time, \( t \)

\( Z \) = Parameter determining the type of crosslink (1<\( Z <3 \))

\( S_I(t) \) = mechanism-based internal state variable quantifying change in crosslink density

### 7.8 Stiffness Degradation Model

#### 7.8.1 Micromechanics based Derivation

From micromechanics of composite materials, for a composite lamina, we have the following relations.

\[ E_1 = E_f V_f + E_m(t) V_m \]

\[ E_2 = \frac{E_f E_m(t)}{E_f V_m + E_m V_f} \]

\[ v_{12} = v_f V_f + v_m(t) V_m \]
where, $E_1$ is the modulus of elasticity of the lamina in the fiber direction

$E_2$ is the modulus of elasticity in the direction transverse to the fiber

$E_f$ is the modulus of elasticity of the fiber

$E_m$ is the modulus of elasticity of the matrix

$V_f$ is the volume fraction of the fiber

$V_m$ is the volume fraction of the matrix

$v_{12}$ is the in-plane Poisson’s ratio of the lamina

$v_{21}$ is the in-plane Poisson’s ratio of the lamina

$v_f$ is the Poisson’s ratio of the fiber

$v_m$ is the Poisson’s ratio of the matrix

$G_{12}$ is the shear modulus of elasticity of the lamina

$G_f$ is the shear modulus of elasticity of the fiber

$G_m$ is the shear modulus of elasticity of the matrix

Also, for a composite lamina, if $[Q]$ is the reduced stiffness matrix in local co-ordinates, we have

$$Q_{11} = \frac{E_1}{1 - v_{12}v_{21}}$$

$$Q_{12} = \frac{v_{21}E_1}{1 - v_{12}v_{21}} = \frac{v_{12}E_2}{1 - v_{12}v_{21}}$$

$$Q_{22} = \frac{E_2}{1 - v_{12}v_{21}}$$

$$Q_{66} = G_{12}$$
7.8.2 Macroscale Derivation for Stiffness

If $[\bar{Q}]$ is the stiffness of the lamina in global co-ordinates, the components of the stiffness matrix are given by

$$\bar{Q}_{11} = Q_{11} \cos^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \sin^4 \theta$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} + 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12}(\sin^4 \theta + \cos^4 \theta)$$

$$\bar{Q}_{22} = Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \cos^4 \theta$$

$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66}) \sin \theta \cos^3 \theta + (Q_{12} - Q_{22} + 2Q_{66}) \cos \theta \sin^3 \theta$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66}) \cos \theta \sin^3 \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta \cos^3 \theta$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{66}(\sin^4 \theta + \cos^4 \theta)$$

where, $\theta$ is the orientation of the fibers in the lamina with respect to global x-direction.

7.8.3 Stiffness degradation due to Hygrothermal Degradation

Hygrothermal degradation primarily affects the polymer matrix in a CFRP. Hence, stiffness degradation occurs through the degradation of matrix properties. The properties of the matrix are affected as follows.

$$E_m(t) = S_H(t)E_{m0}$$

$$G_m(t) = S_H(t)G_{m0}$$

$$\nu_m(t) = S_H(t)\nu_{m0}$$

where, $S_H(t)$ is the ISV for hygrothermal degradation as discussed earlier.

$E_{m0}$ is the modulus of elasticity of the polymer matrix before degradation.

$G_{m0}$ is the shear modulus of elasticity of the polymer matrix before degradation.

$\nu_{m0}$ is the Poisson’s ratio of the polymer matrix before degradation.
7.8.4 Stiffness degradation due to Thermal Degradation

The properties of the polymer matrix are affected due to thermal degradation as,

\[ E_m(t) = S_T(t)E_{m0} \]
\[ G_m(t) = S_T(t)G_{m0} \]
\[ v_m(t) = S_T(t)v_{m0} \]

where, \( S_T(t) \) is the ISV for thermal degradation as discussed earlier.

- \( E_{m0} \) is the modulus of elasticity of the polymer matrix before degradation.
- \( G_{m0} \) is the shear modulus of elasticity of the polymer matrix before degradation.
- \( v_{m0} \) is the Poisson’s ratio of the polymer matrix before degradation.

7.9 Strength Degradation Model

7.9.1 Compressive Failure

Using the failure strain data obtained from flexure tests, an ISV is calculated and it is used to degrade the strength. For hygrothermal degradation, we have

\[ \epsilon_c(t) = S_H(t)\epsilon_{c0} \]

where \( \epsilon_c(t) \) is the compressive failure strain after ageing time \( t \) in a flexure specimen.

- \( \epsilon_{c0} \) is the compressive failure strain before degradation.
- \( S_H(t) \) is the ISV for hygrothermal degradation calculated using the existing data.

Similarly, for thermal degradation, we have

\[ \epsilon_c(t) = S_T(t)\epsilon_{c0} \]

where \( \epsilon_c(t) \) is the compressive failure strain at ageing time \( t \).

- \( \epsilon_{c0} \) is the compressive failure strain before degradation.
- \( S_T(t) \) is the ISV for thermal degradation calculated using the existing data.
7.9.2 Failure through delamination at the interface between adjacent lamina

Similar to compressive failure, an ISV for delamination failure is determined using the critical von Mises stress data (refer to Chapter 6 for details). For the case of hygrothermal degradation, the critical von-Mises stress is assumed to degrade in the following manner based on the hygrothermal degradation mechanism discussed earlier in this chapter,

\[ \sigma_{VM}(t) = S_H(t)\sigma_{VM0} \]

where \( \sigma_{VM}(t) \) is the critical von Mises stress after ageing time \( t \)

\( \sigma_{VM0} \) is the critical von Mises stress before degradation

\( S_H(t) \) is the ISV for hygrothermal degradation calculated using the existing data

Similarly, for thermal degradation,

\[ \sigma_{VM}(t) = S_T(t)\sigma_{VM0} \]

where \( \sigma_{VM}(t) \) is the critical von Mises stress after ageing time \( t \)

\( \sigma_{VM0} \) is the critical von Mises stress before degradation

\( S_T(t) \) is the ISV for thermal degradation calculated using the existing data

7.10 Composite Performance Prediction Tool (CPPT)

The CPPT software has been programmed using Visual Basic. This has facilitated in creation of a graphical user interface (GUI). The user interface has been designed to make it as easy as possible for a field engineer to use, without recourse to complex Finite Element Analysis. The software has three main screens: a home screen, an input screen and an output screen.

The input parameters are categorized into various types and assigned a separate tab for each category to make the software user friendly.
Structural Geometry Input

Figure 7.10 shows the input screen for structural geometry. It has input fields to enter the dimensions of the loaded structure such as length, width and thickness.

![Structural Geometry Input Screen](image)

Figure 7.10: Structural Geometry Input Screen

Type of loading Input

Figure 7.11 shows the input screen for type of loading. The user has a choice to select either concentrated or distributed loading. Magnitude of load is to be entered for concentrated loading case. In case of distributed loading, the user needs to enter the magnitude of load per unit length.
Environmental Conditions Input

The environmental conditions to which the composite will be subjected can be selected in this input screen, as shown in Figure 7.12. The user has a choice to select from options like desert, coastal, arctic or tropical environment. The test conditions corresponding to each environment are assumed as desert (70°C and 0% RH), coastal (50°C and 100% RH), arctic (50°C and 0% RH) and tropical (70°C and 100% RH).
Figure 7.12: Input screen for environmental conditions

Material properties Input

The input screen for material properties input is shown in Figure 7.13. It has input fields to enter elastic moduli of fiber and resin, Poisson’s ratio of fiber and resin and the fiber volume fraction.
Similar tabs are present for other input categories. The inputs required for calculation of parameters for damage due to moisture diffusion are included in a separate tab. Laminate specification includes the number of layers of fiber and the orientation of each layer. And finally, the user can choose the analysis type where in the allowable load for a given service life or the time to failure under given loading conditions can be calculated.

The software then performs the calculations as depicted in the flow chart in an earlier section (section 7.3-7.9). The calculated results are then displayed on the output screen. A sample output screenshot is shown in Figure 7.14.
Figure 7.14: Screenshot of output screen
CHAPTER 8

CONCLUSIONS

Synergistic effect of environmental ageing on the degradation of interlaminar shear strength of carbon-epoxy composite specimens was studied. Laminates of [0]_{30} configuration were fabricated using VARTM process and machined into coupons. The coupons were subjected to accelerated ageing under various combinations of humidity (0% RH and 100% RH), temperature (50°C and 70°C) and applied stress (0% UTS and 5% UTS). Mechanical testing was conducted on the specimens in order to determine the interlaminar shear strength (ILSS) of the composite. Tests were conducted at room temperature, according ASTM D2344-84, at a displacement rate of 0.05 in/min. Ageing was carried out for three time intervals and test data were collected for each ageing condition at each ageing time. The results of the aged specimens were compared with the unaged specimens in order to see the effect of environmental degradation.

From the experimental results, it was clear that moisture had a dominant role to play in the degradation of ILSS of the composite specimens. Moisture, accompanied by stress, had the greatest effect, leading to fastest degradation compared to other conditions. Temperature did not have a major effect on strength degradation. Wet specimens on an average lost about 22.8% strength. Dry specimens on the other hand gained a marginal 0.5% in strength, probably due to post curing effect. It was also observed that the degradation occurred only till the moisture saturation of the wet specimens. After that, further ageing did not alter the strength significantly.
Once the experiments were completed, finite element modeling was performed in order to simulate the experimental results for each case. A unique viscoelastic cohesive layer approach was followed to simulate the delaminations observed in the experiments. An in-house FORTRAN based FEA code, NOVA-3D, was employed for this purpose.

The viscoelastic cohesive layer approach helped overcome the numerical instabilities that usually occur at the point of failure. The simulated load vs. displacement curves matched well with the experimental results. An error of about 6% was observed in the peak load prediction for unaged specimens. For all the other conditions, the error was less than 10%. Thus, the FEA model was quite accurate.

The final objective of the research was to develop a PC based software tool, which could predict the life of the composite structure. Programming was done in Visual basic. A mechanism based degradation model was used to predict the number of cross links remaining in the polymer matrix after a given ageing time and was correlated to strength degradation. The unknown parameters in the model were determined using the data obtained in experiments and modeling. The software was able to predict the life of the tested specimens with acceptable accuracy for both delamination and compressive (flexure) failure. The software can be modified to predict life for other fiber and resin combinations.
REFERENCES


Roy Samit and Yong Wang, "Analytical solution for cohesive layer model and model verification." Polymers and Polymer Composites (2005): 741-752


